Superconducting Magnets for Neutrino Factory Storage Ring Study 2

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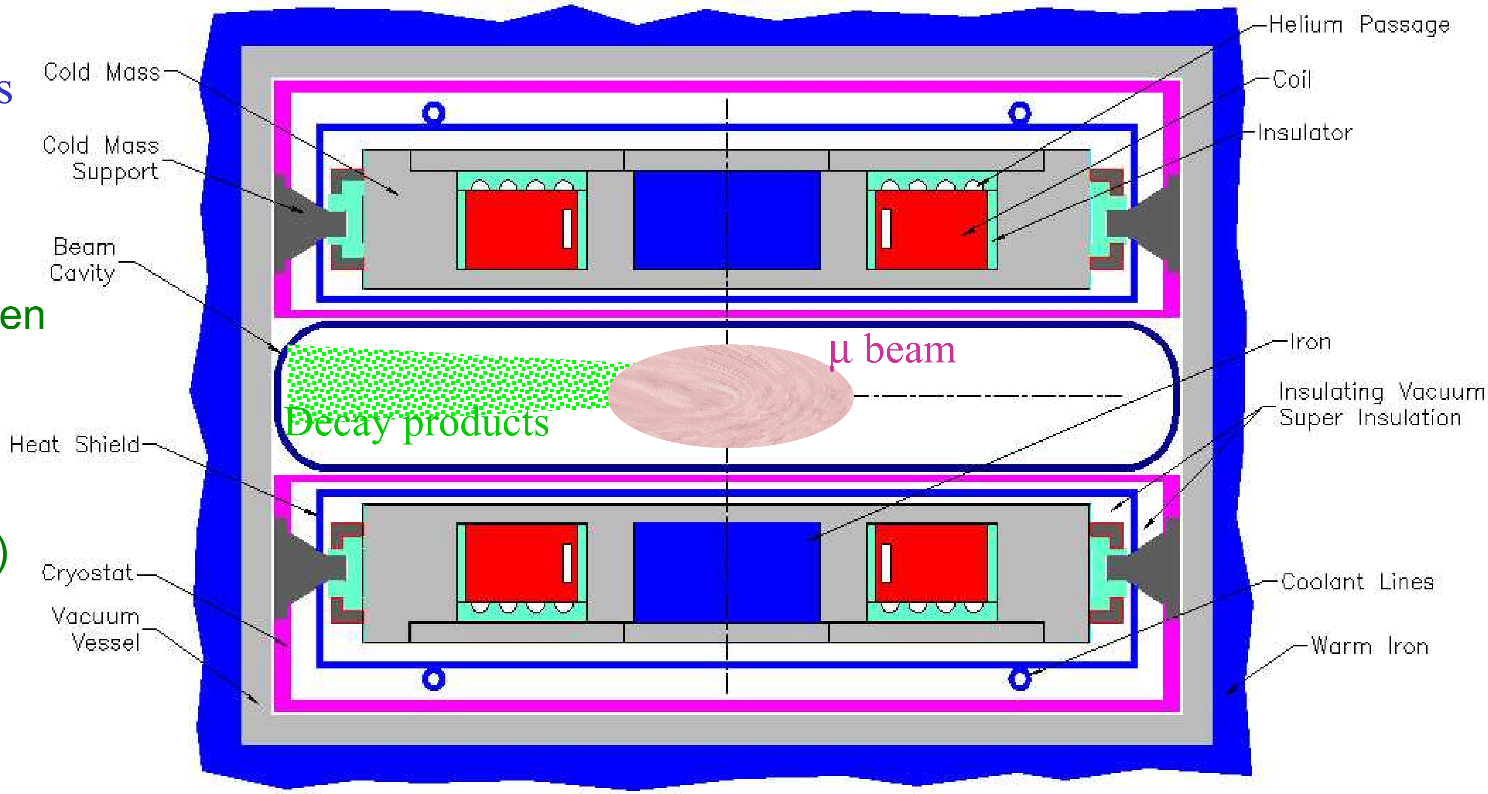
Magnet Design for ν Factory Storage Ring Study II

Simple racetrack coils with open midplane (does not require Tungsten liner)*

The following design is for ν Factory but the principles are relevant to muon collider also

Decay products clear superconducting coils

*Earlier studies on open midplane design by **P. McIntyre** and by **M. Green** (with some variations)



HTS is an interesting possibilities in such magnets.

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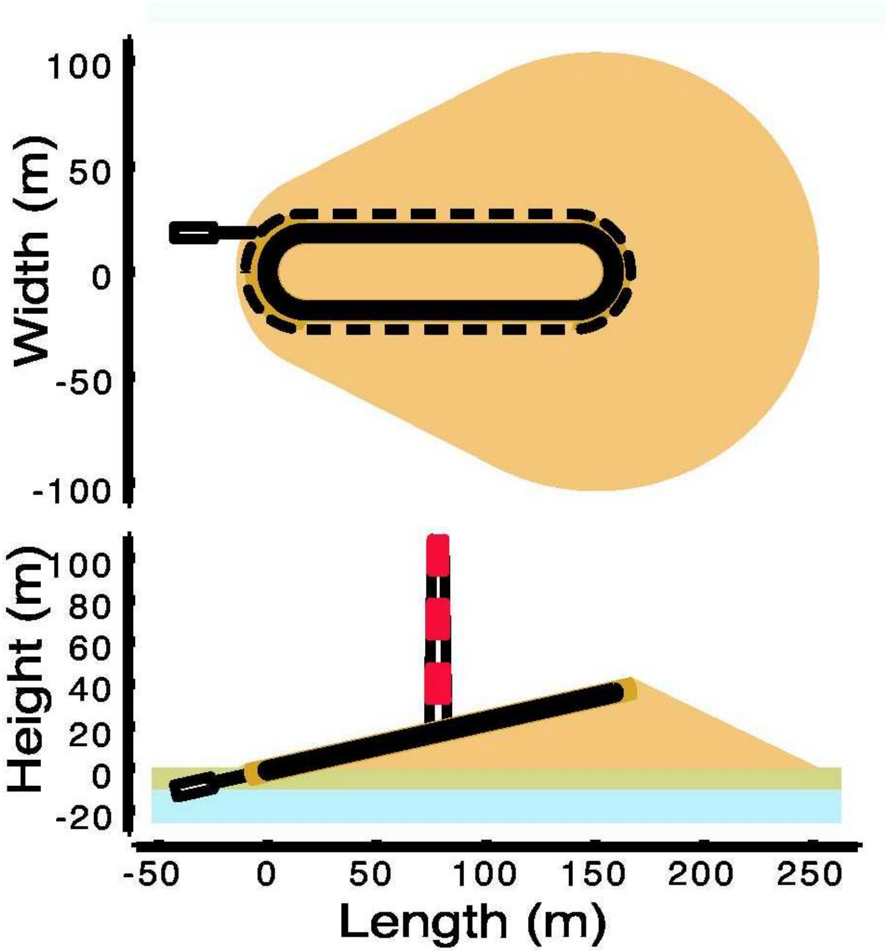
Issues Related to BNL Site for ν Factory Storage Ring Study II



The machine must be tilted.

The storage ring would go underground and above ground.

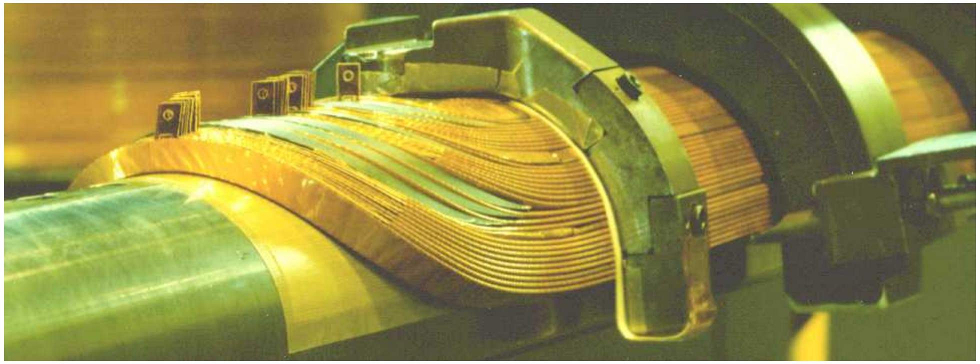
The issue of drinking water table

a bit sensitive issue for BNL site.

Should make compact ring to the minimize the environmental impact.

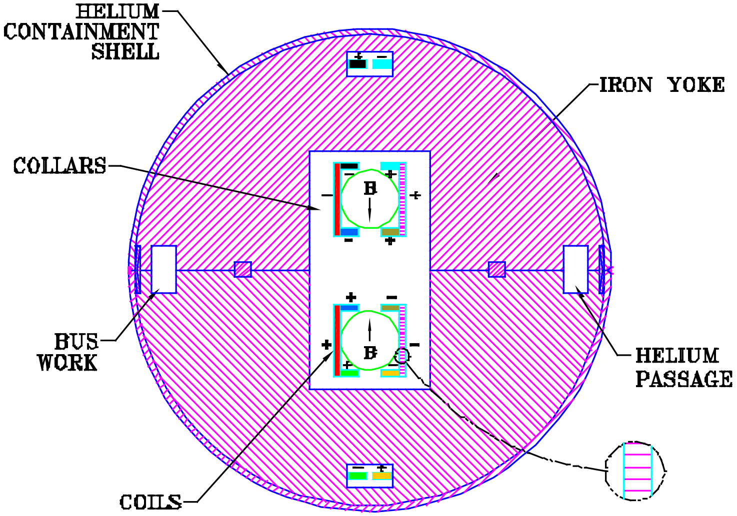
⇨ Need high field magnets & efficient machine + magnet system design

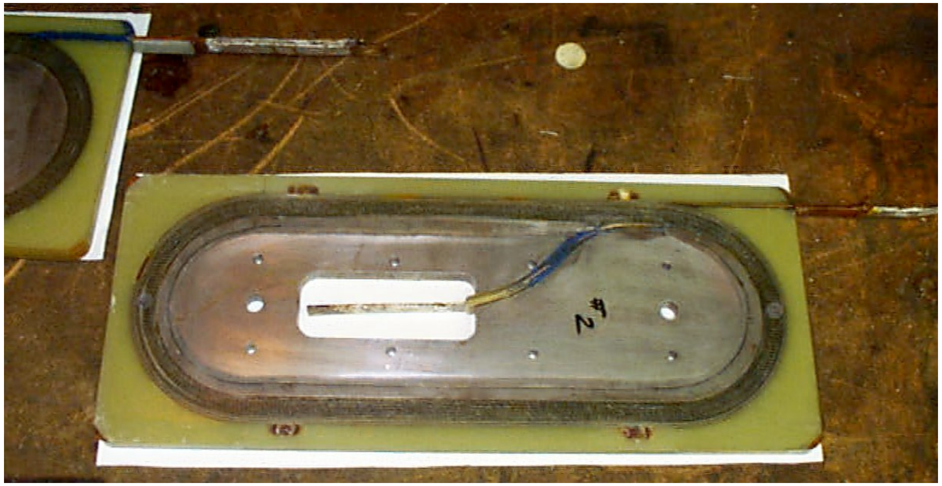
Racetrack Coil Magnets for High Fields

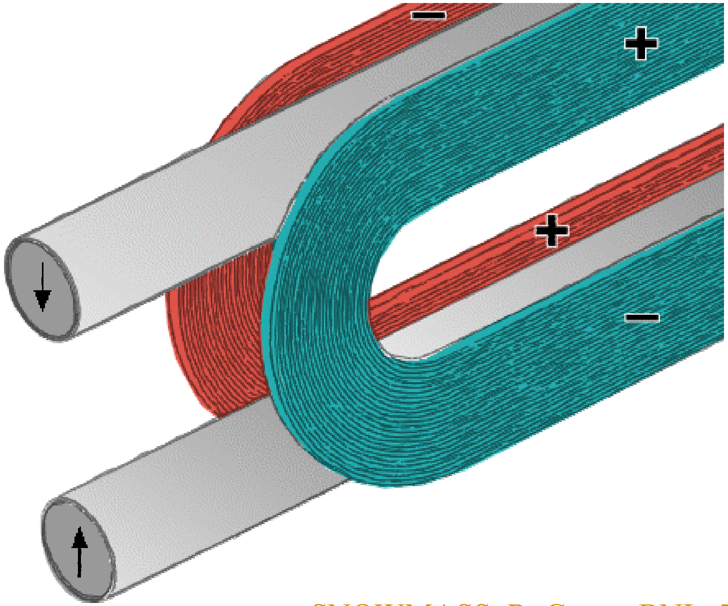


Conventional cosine θ design (e.g., RHIC magnets)

Complex 3-d geometry -- not best for high fields





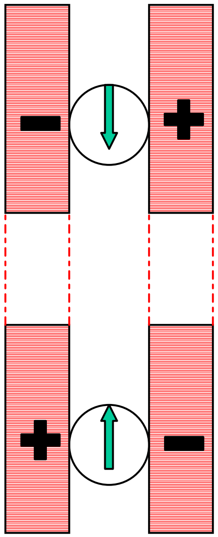


Conductor friendly racetrack coil geometry

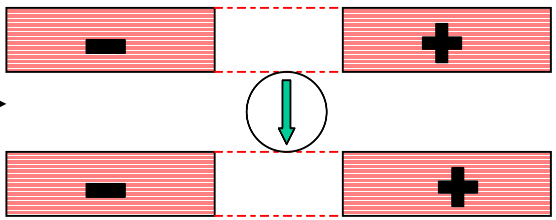
Suitable for high field magnets with brittle material

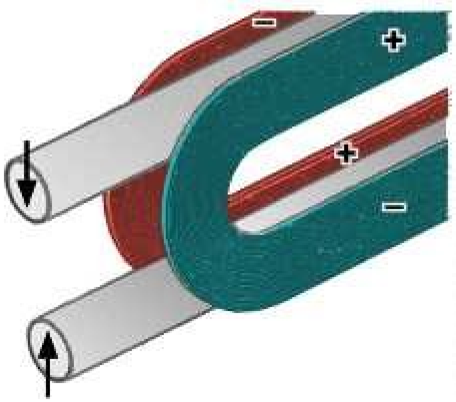
Common Coil and Muon Collider Test Configurations

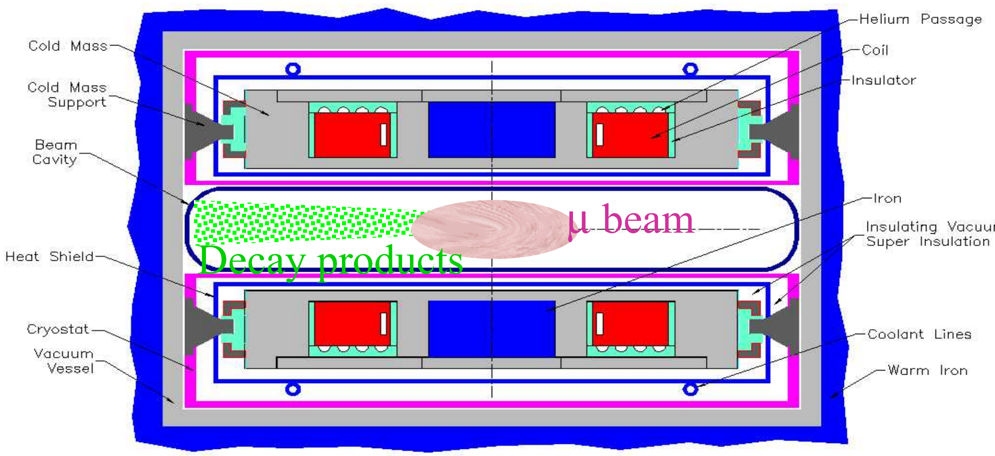
Common Coil configuration | **muon collider configuration**



Powering differently changes common coil design test to muon collider design test







Racetrack Coil Magnets for High Fields

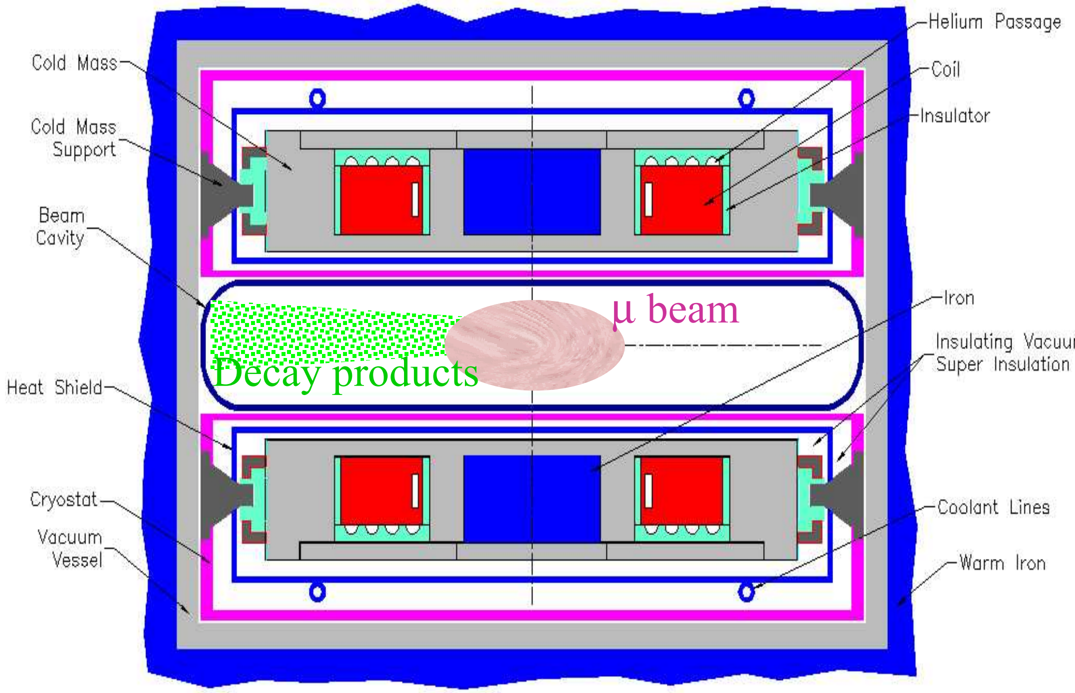
Design Issues:

- Must use brittle materials

  Nb_3Sn, HTS

- Large Lorentz forces
- Large energy deposition
- Cold coils, Warm iron
- Need compact cryostat
- Large heat leak

Racetrack coils with open midplane* to minimize muon decay products directly hitting SC coils (does not require Tungeston liner)



Conductor friendly racetrack coil geometry

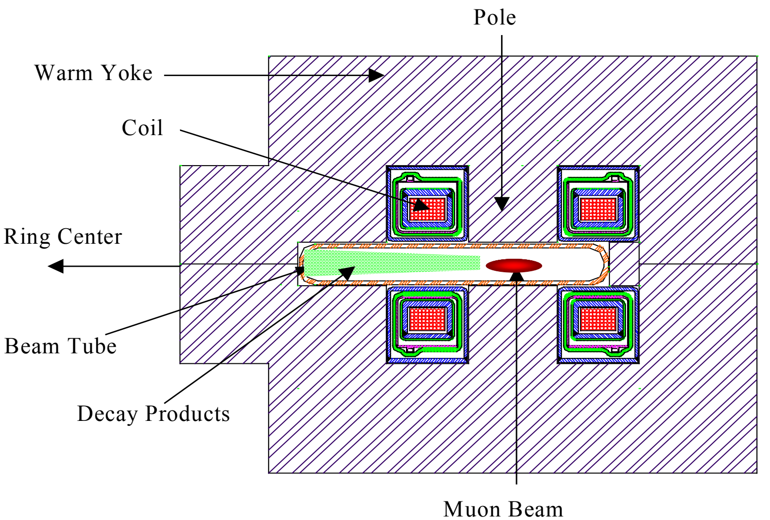
Suitable for high field magnets with brittle material

HTS is an interesting possibilities in such magnets.

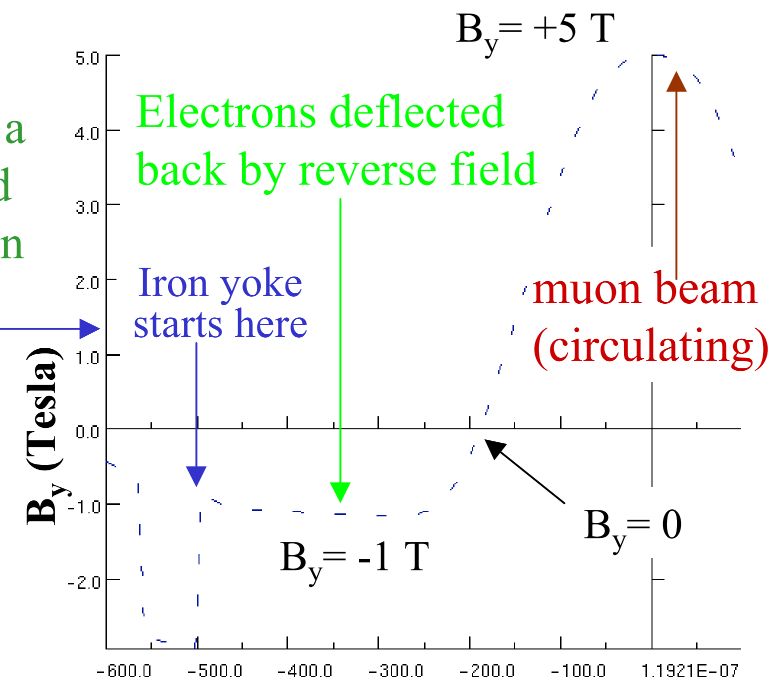
5 T Dipole for ν Storage Ring

5 T central field can be achieved by NbTi

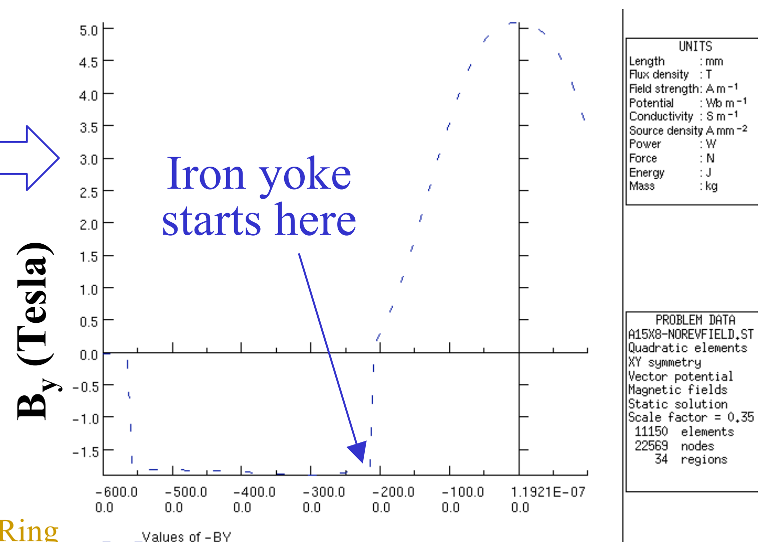
Decay electrons get back towards main aperture by
(a) Reverse field and (b) Magnet saggitta
which knob to use how much may depend on E & B



Design with a reverse field region in Iron



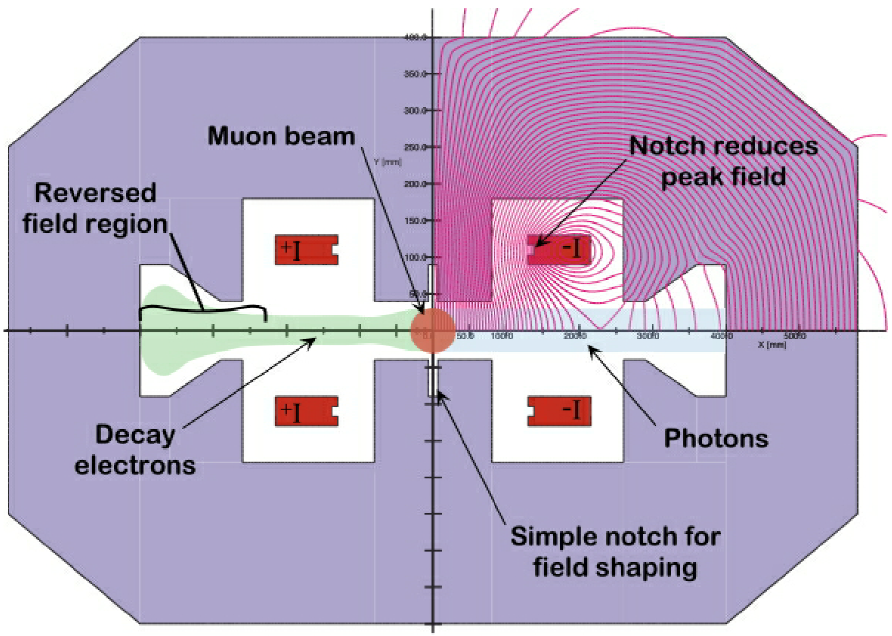
A dipole with no cutout in yoke for a reverse field region. Electrons will hit yoke and create shower



In neutrino storage ring, is ~10% energy deposition acceptable?

Magnetically Optimized Design

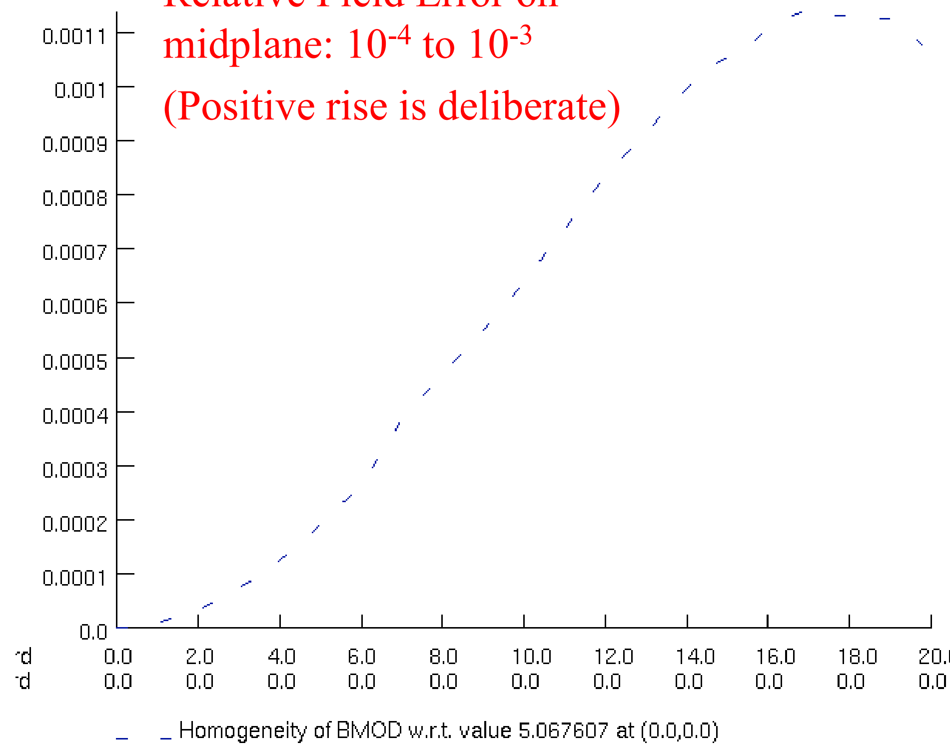
Cutout in yoke to optimize field quality: Model used in MARS Studies (Brett Parker)



Toy model dipole with improved field harmonics and extended vertical cutout.

Relative Field Error on midplane: 10^{-4} to 10^{-3}

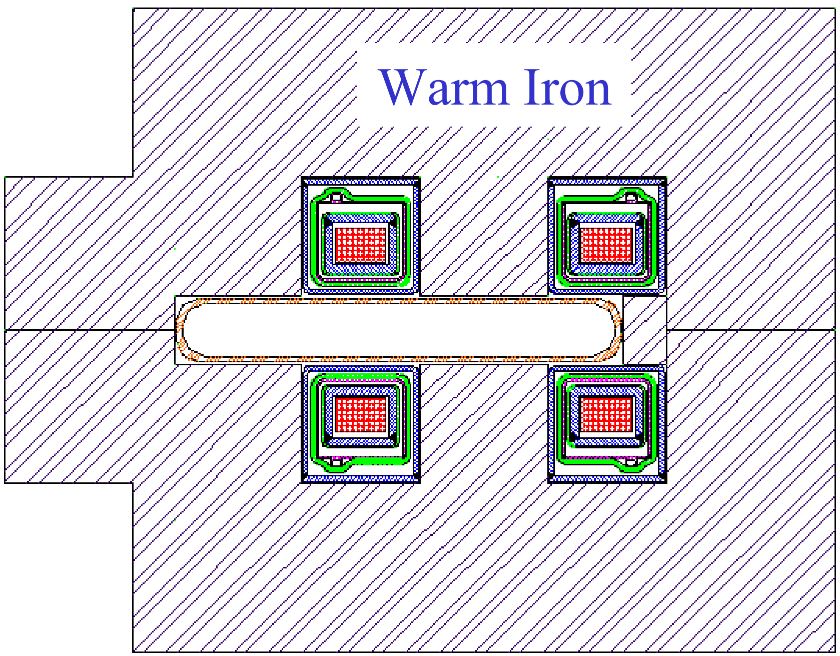
(Positive rise is deliberate)



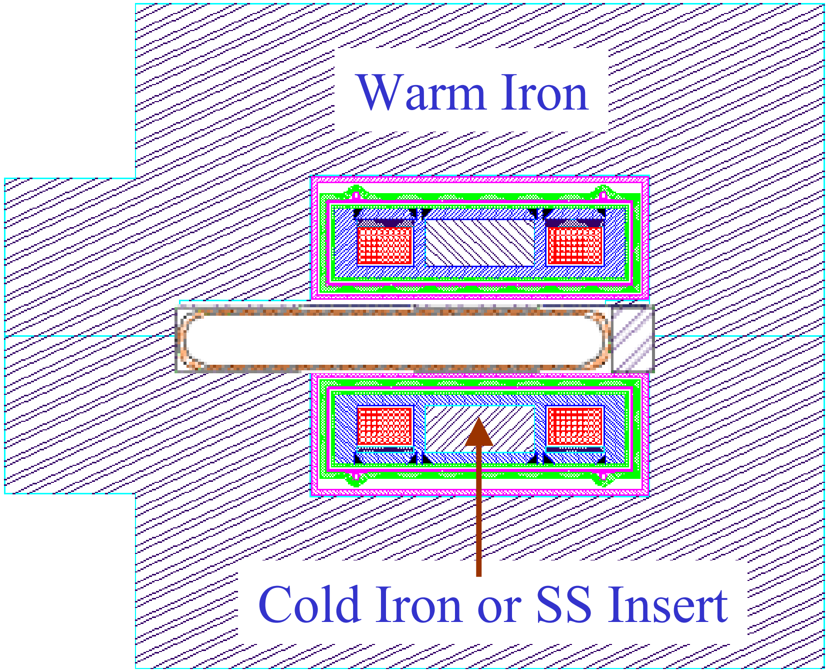
Magnet Design Evolution

Common cryostat for two coil halves:

For a better mechanical and cryogenic design



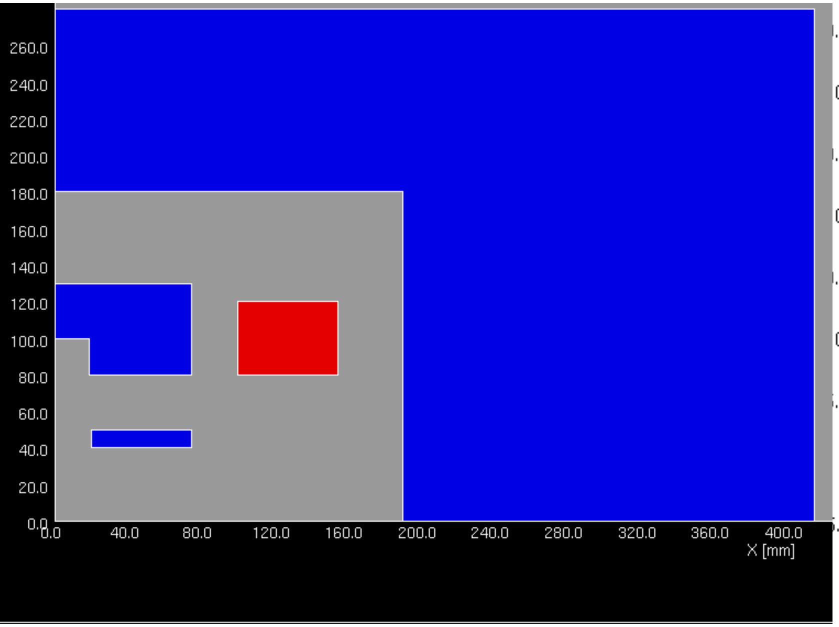
Very Earlier Version

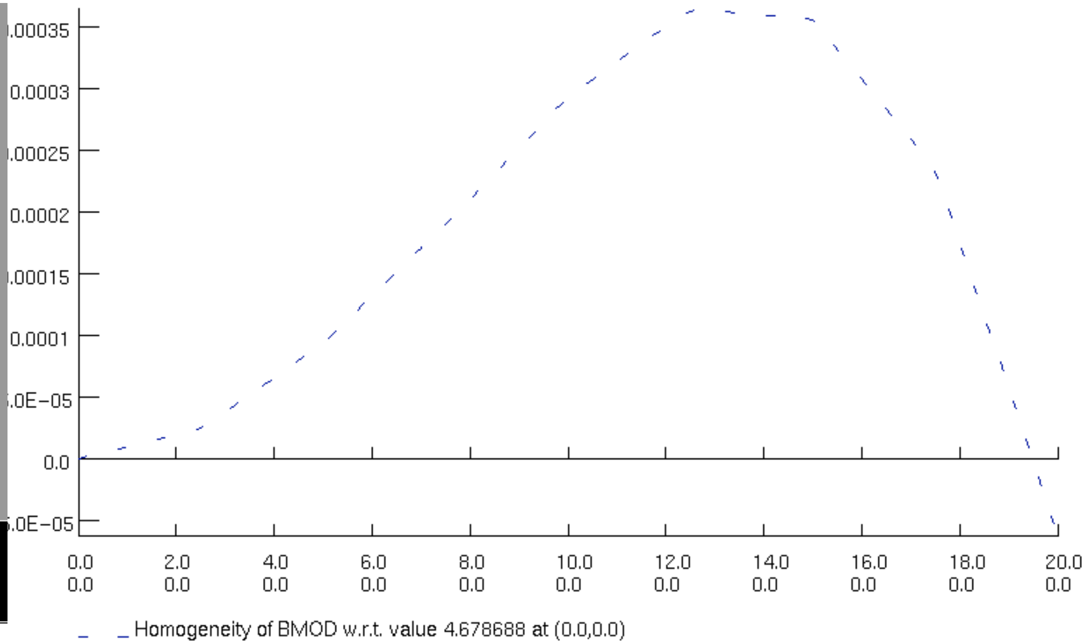


Intermediate Version

Magnetically Optimized Design

Preliminary optimized design for field quality





Relative Field Error on midplane: ~10^{-4} to 10^{-3}

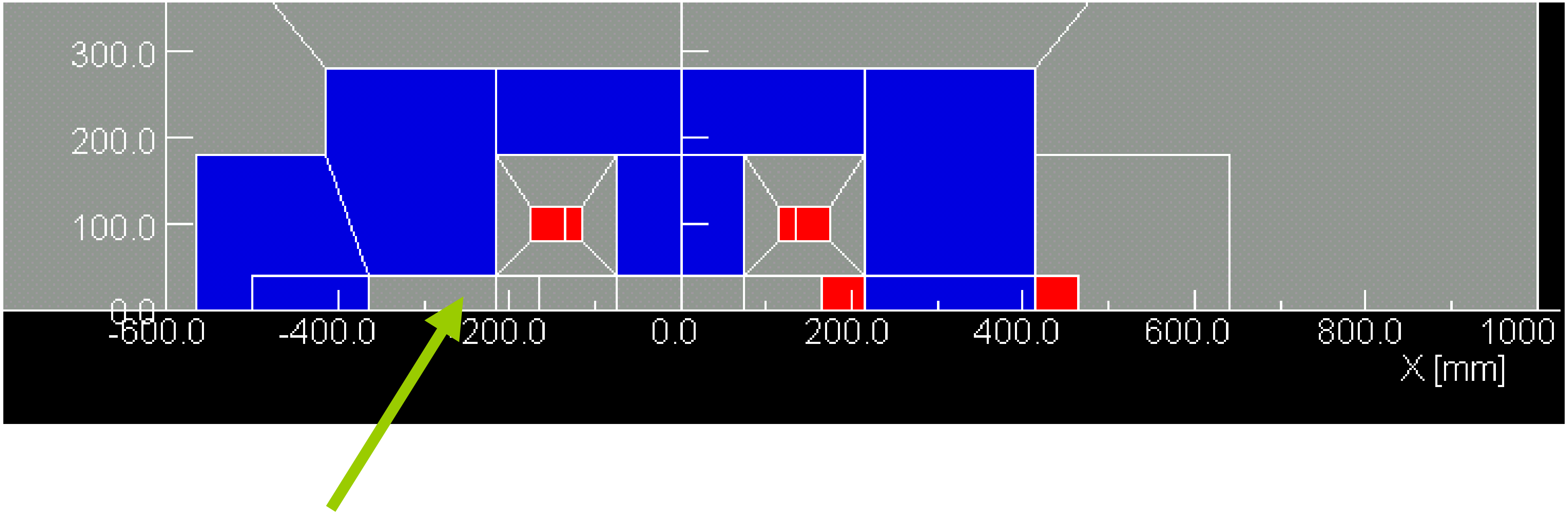
(Positive rise on midplane is deliberate)

Normal Combined Function Magnet

A combined function magnet design without decay product hitting the coils

Central field increases

Only one type of combined function magnet possible



Most decay product are on one side

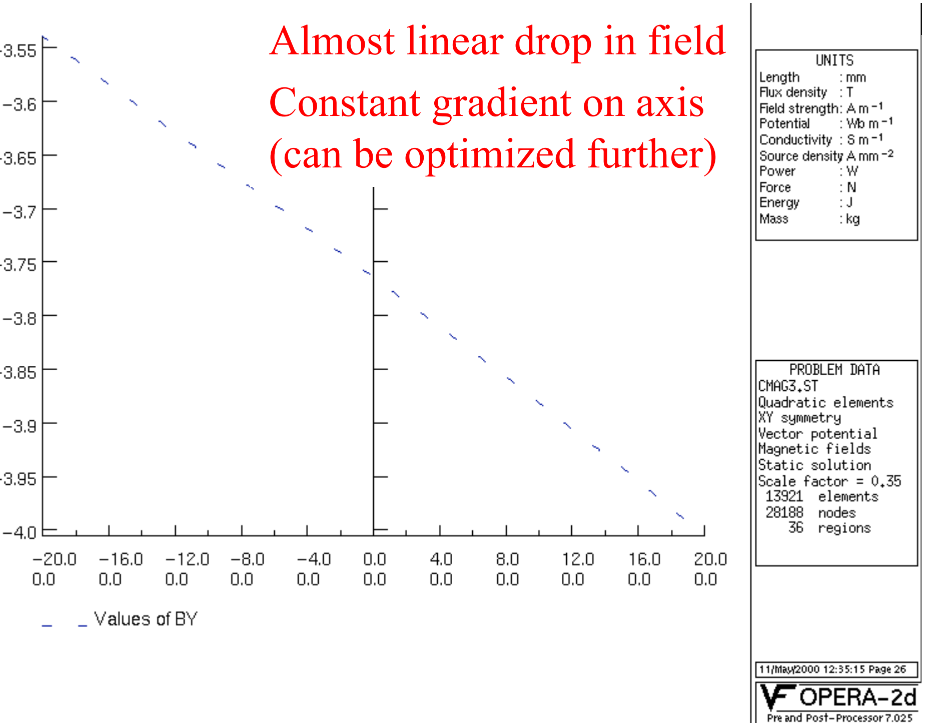
Possibility of A Combined Function Magnet Design

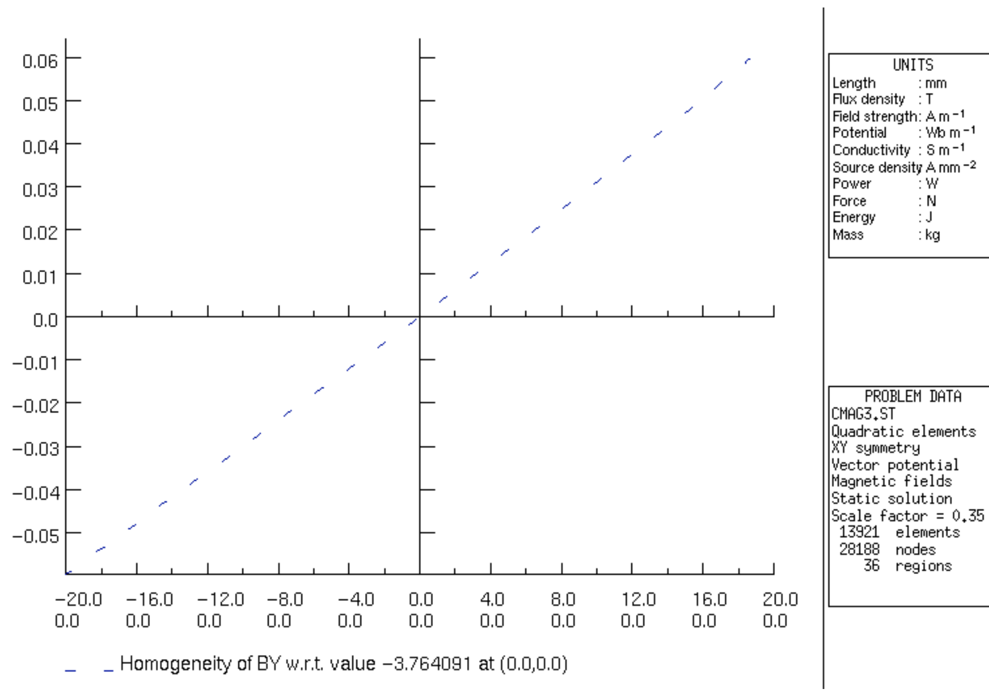
Since, most energy deposition is on one side, the coil on other side can be brought closer to midplane, or one can have a "C magnet". This generates a combined function magnet, actually with a higher field. But with only of one type of focussing. Imagine a lattice where long dipole have focussing of one kind and the other type of focussing comes from traditional quadrupoles. AP Issues?

Dipole (F)	QD	Dipole (F)	QD	Dipole (F)	QD

Almost linear drop in field

Constant gradient on axis (can be optimized further)

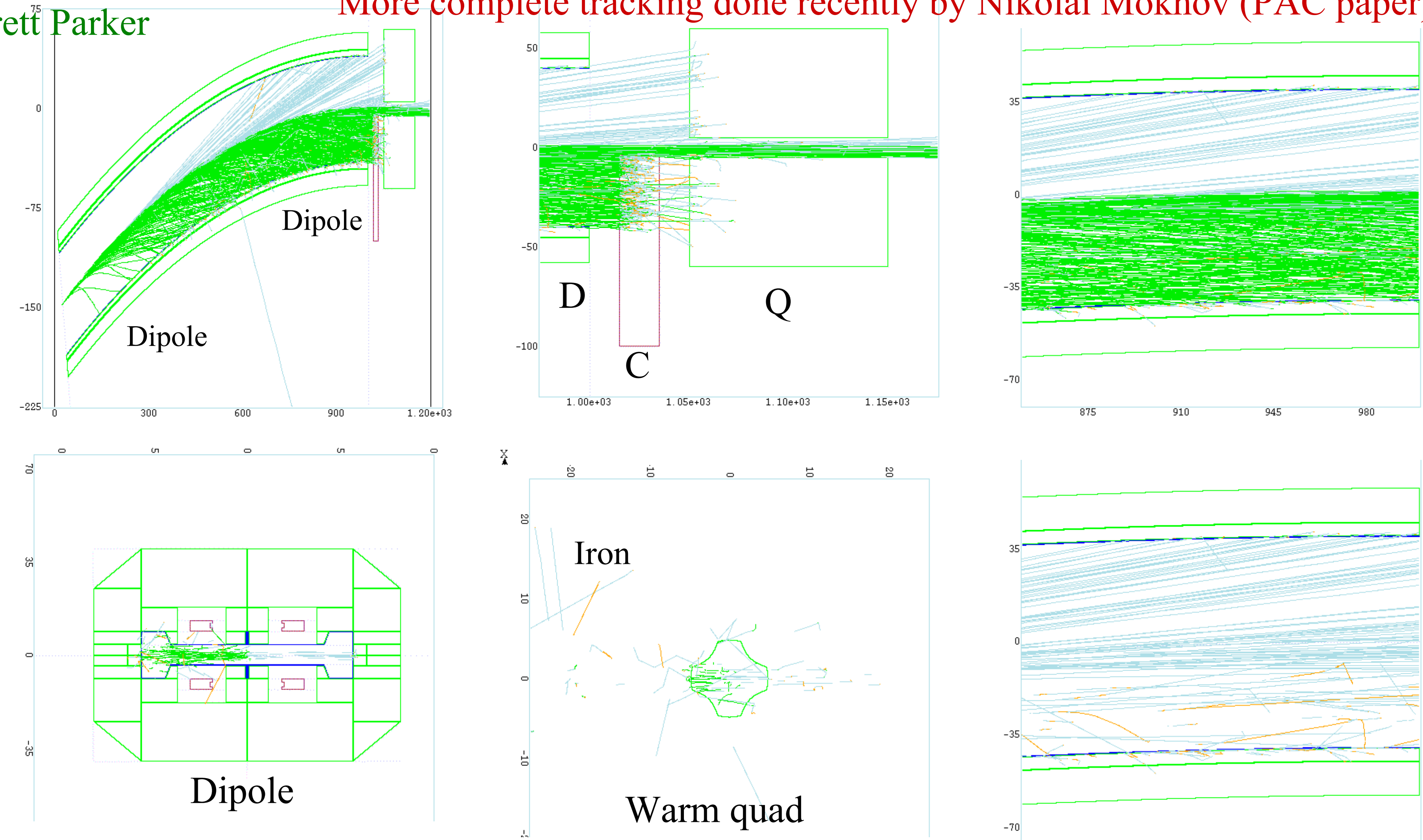




Preliminary Particle Tracking with MARS for Neutrino Storage Ring Magnets

Brett Parker

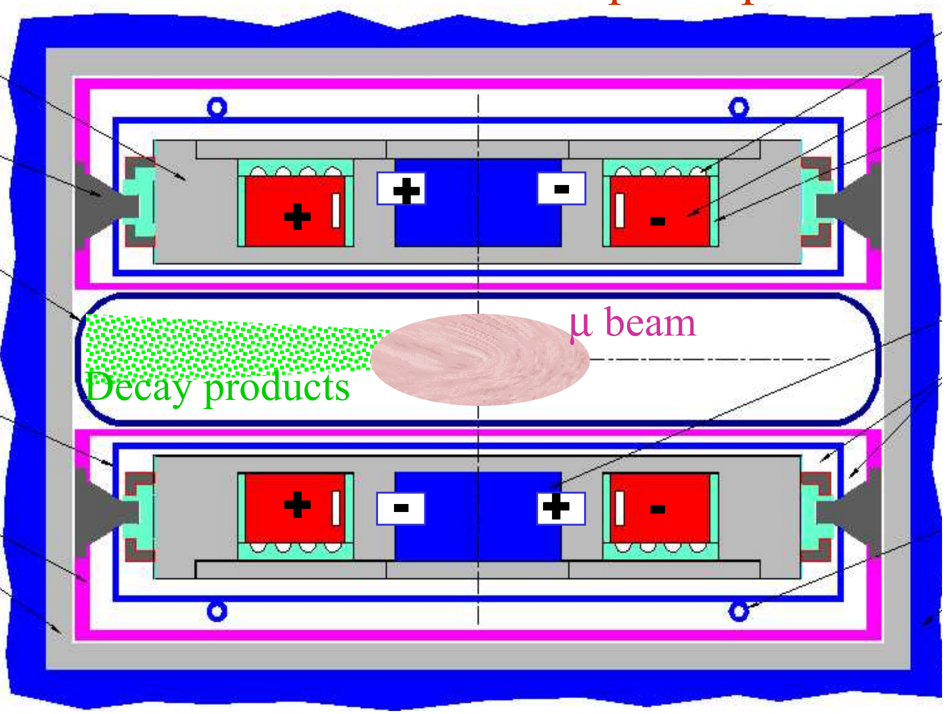
More complete tracking done recently by Nikolai Mokhov (PAC paper)



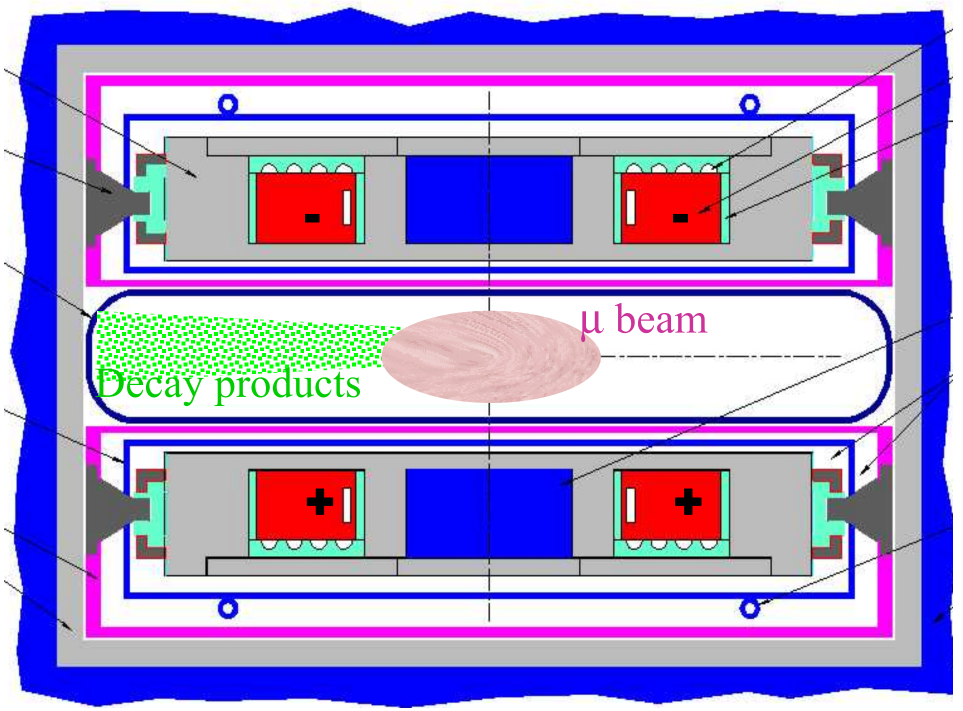
Skew Quadrupole Lattice

Brett Parker: Skew quadrupole clears midplane

Combined function skew quadrupole



Skew quadrupole



However, the strength requirement turned out to be so large that the central field in combined function dipole reduced by a large amount (peak field in coil goes up).

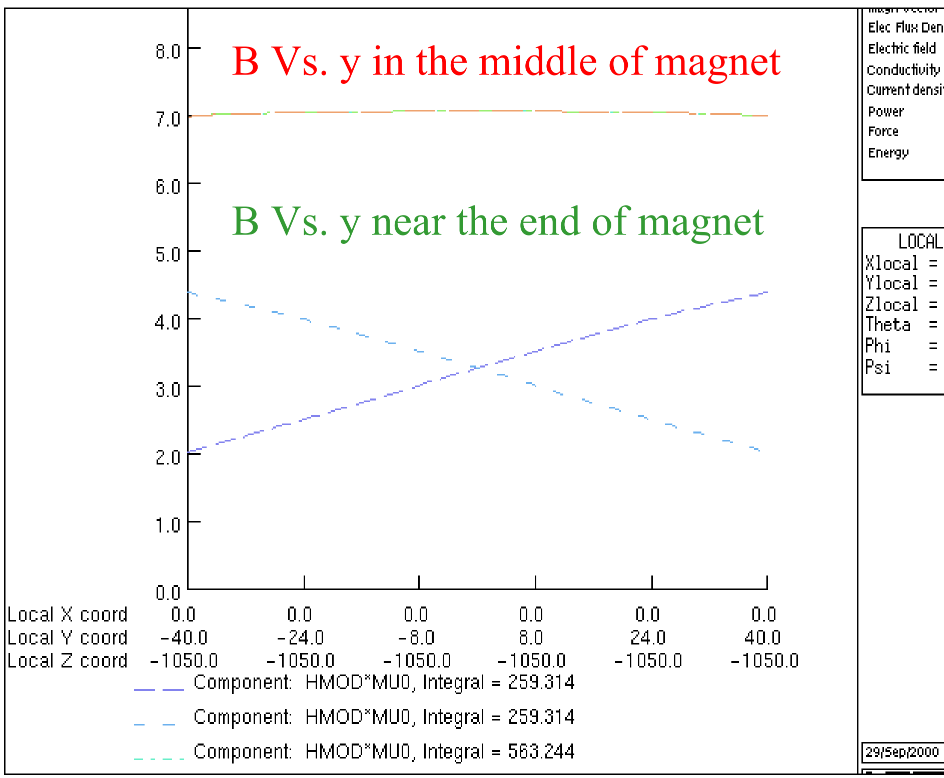
In separated function magnets, a large fraction of space is lost in interconnects due to small length and large aperture of the magnets.

Skew Quad Lattice by Axially Shifting Coils

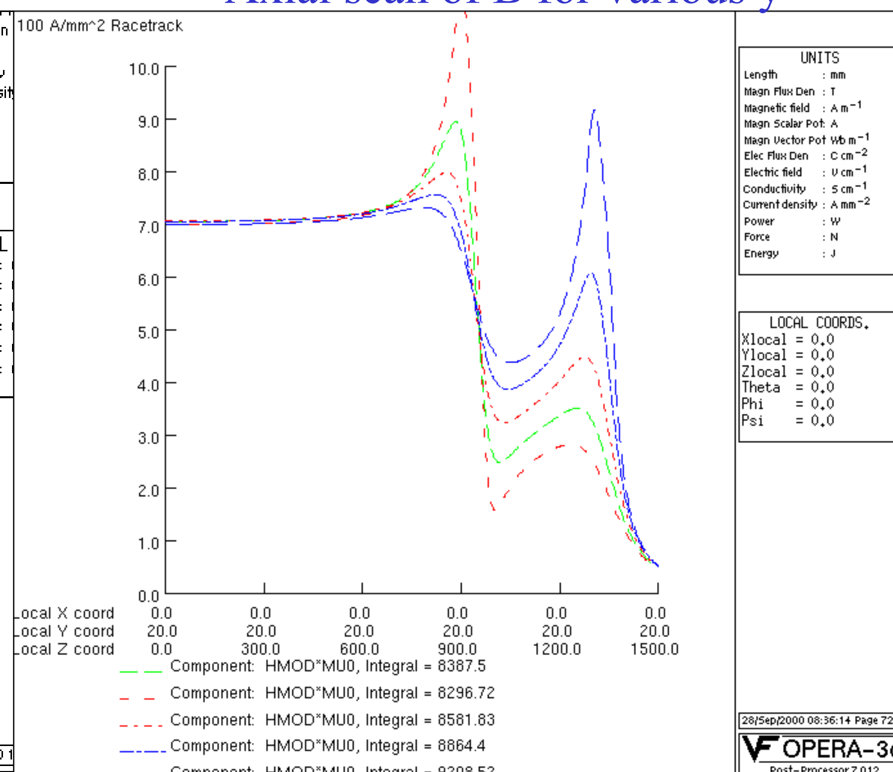
Dipole section

Combined function magnet section

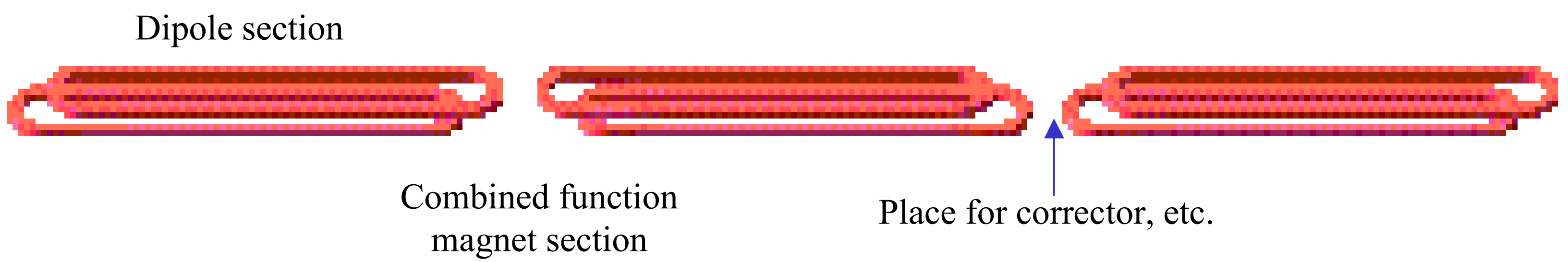
Place for corrector, etc.

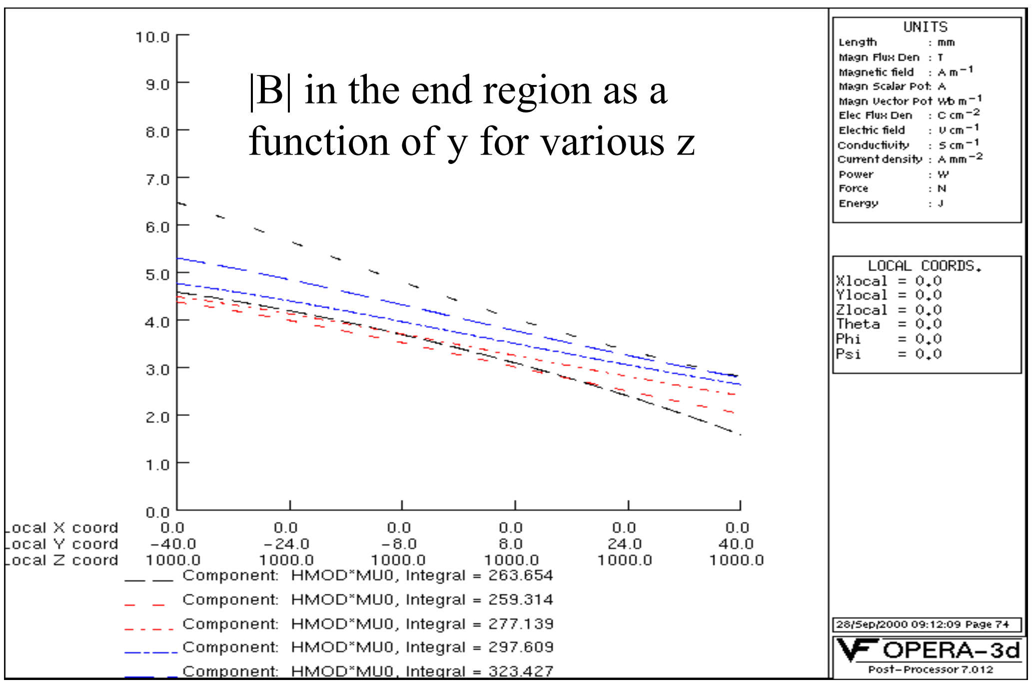


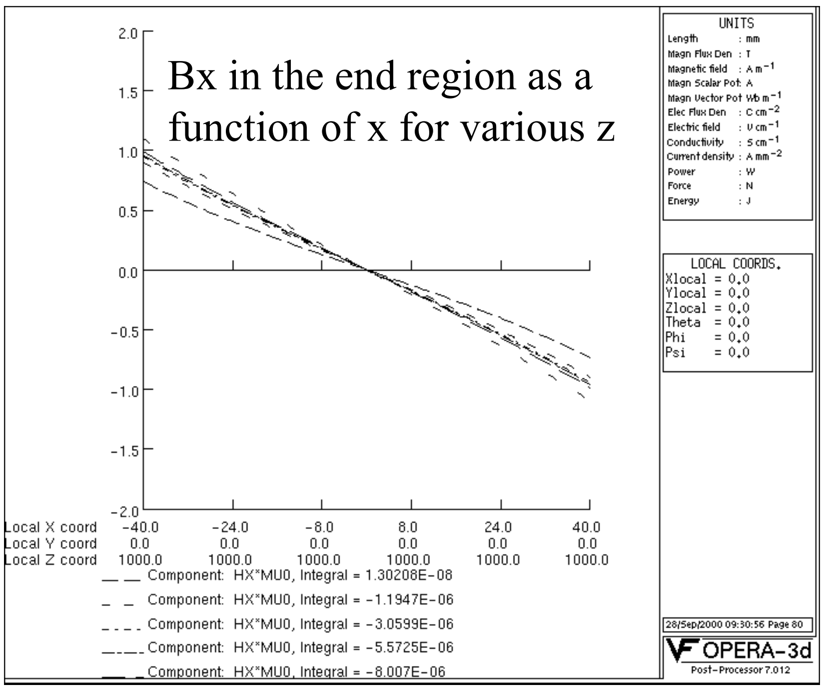
Axial scan of B for various y



Skew Quad Lattice by Axially Shifting Coils







Getting Rid of Half Ends/Interconnects

Dipole section

Combined function magnet section

Place for corrector, etc.

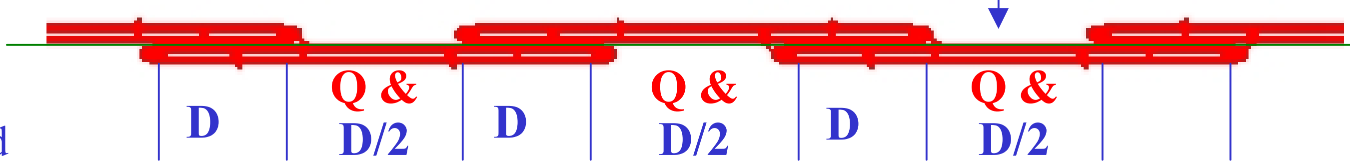
Bob Palmer suggested making coils twice as long and thus getting rid of half ends and interconnects

Place for corrector, etc.

(access from one side only)

Quadrupole(Q): Field Gradient

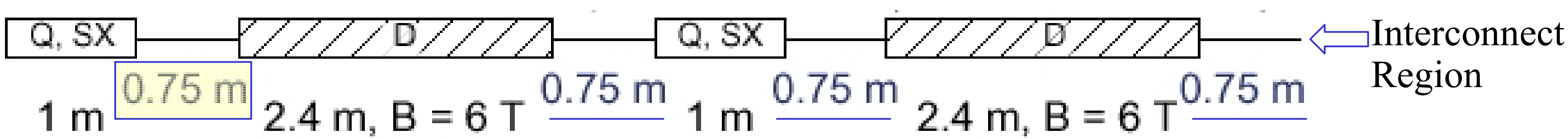
Dipole(D): Field



No space is wasted for interconnect

Lattice & Magnet Designs for a Compact Ring

- Skew quadrupole needs NO conductor at midplane (B. Parker)
- In study 1 (50 GeV), ~1/3 space was taken by inter-connect regions

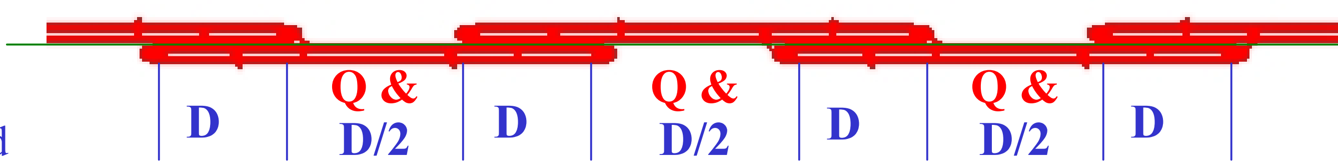


Gets worse at lower energy (50 => 20 GeV in study 2)

- New magnet system design makes a productive use of all space

Quadrupole(Q): Field Gradient

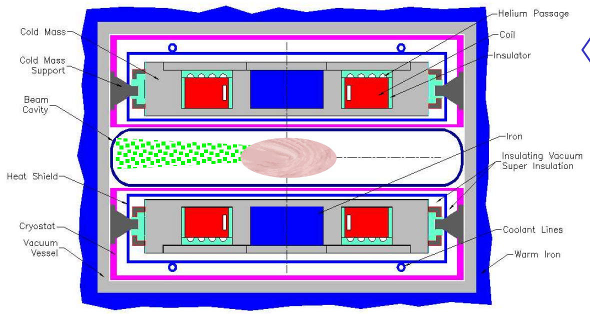
Dipole(D): Field



No space is wasted for interconnect

Shorter cells ⇨ smaller aperture, improved beam dynamics

Modified Cross-section for Better Field Quality



This cross-section gives ~50 units of sextupole

Initially assumed OK for ~1000 turn

Beam Physicists demanded better field quality

All harmonics ~1 unit at 20 mm radius are obtained by taking coil horizontally further out

Penalty for such a design:

A higher peak field (~+50%); can be reduced by proper grading and reducing current density.

Rough argmument: center of the coil should be ~30 degree for zero sextupole

Saturation-induced harmonics are small. Not so important for fixed field magnets, but a small value allows some adjustment in field, if needed.

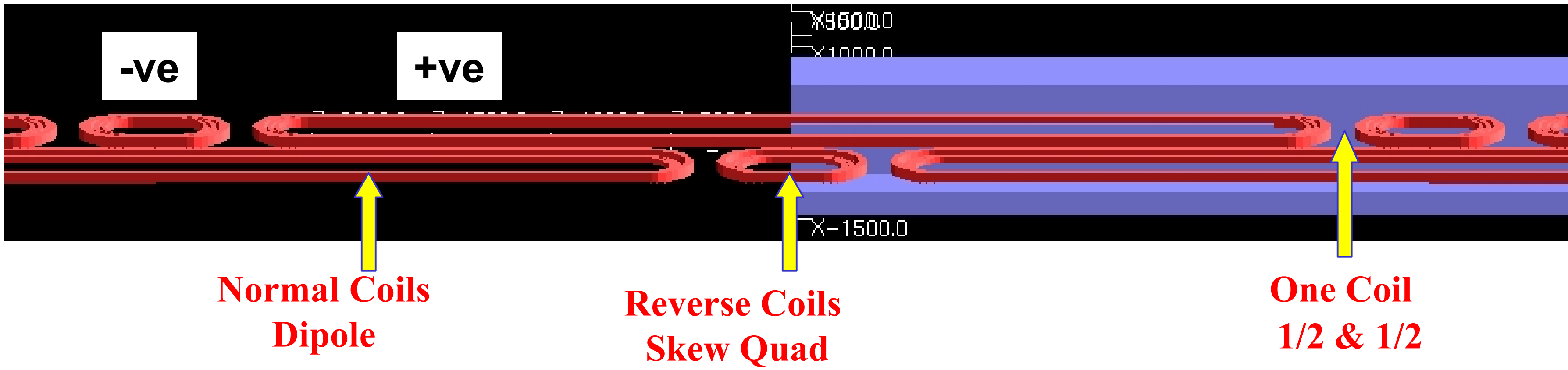
Penalty for making good field quality: A substantial increase in vertical Lorentz forces.

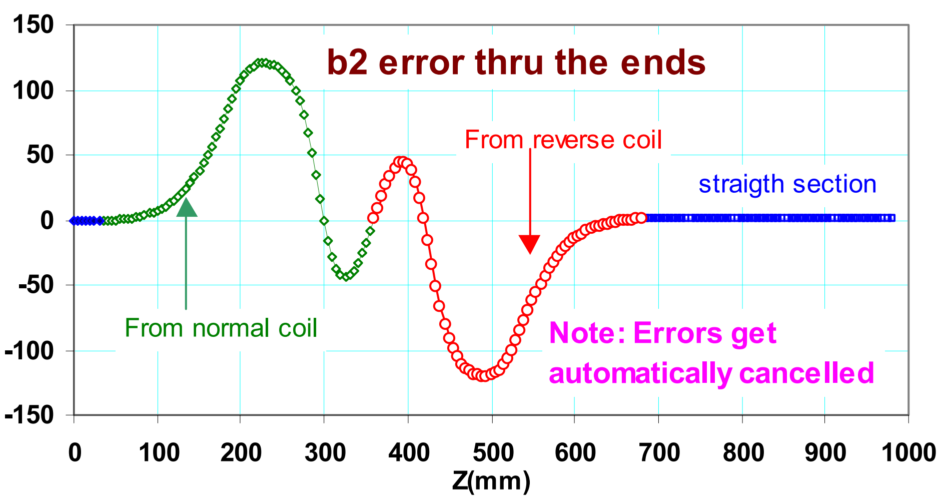
However, it still leaves field quality issues in the magnet ends

- Conductor at the pole give negative b2 and conductor at midplane negative b2.
- Typically, we take midplane conductor further out to compensate for extra conductor at the pole that must be present in the conventional ends.
- Here we do not have midplane conductor to provide that compensation for zero integral b2.

Alternate End Design Concept

- Reverse coils to cancel field harmonics in ends (also generate skew quad)





New Magnet System Design

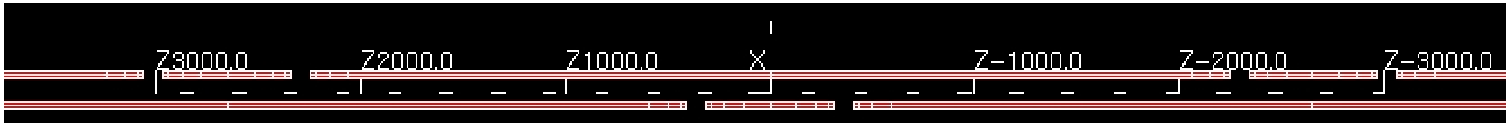
> Good field quality

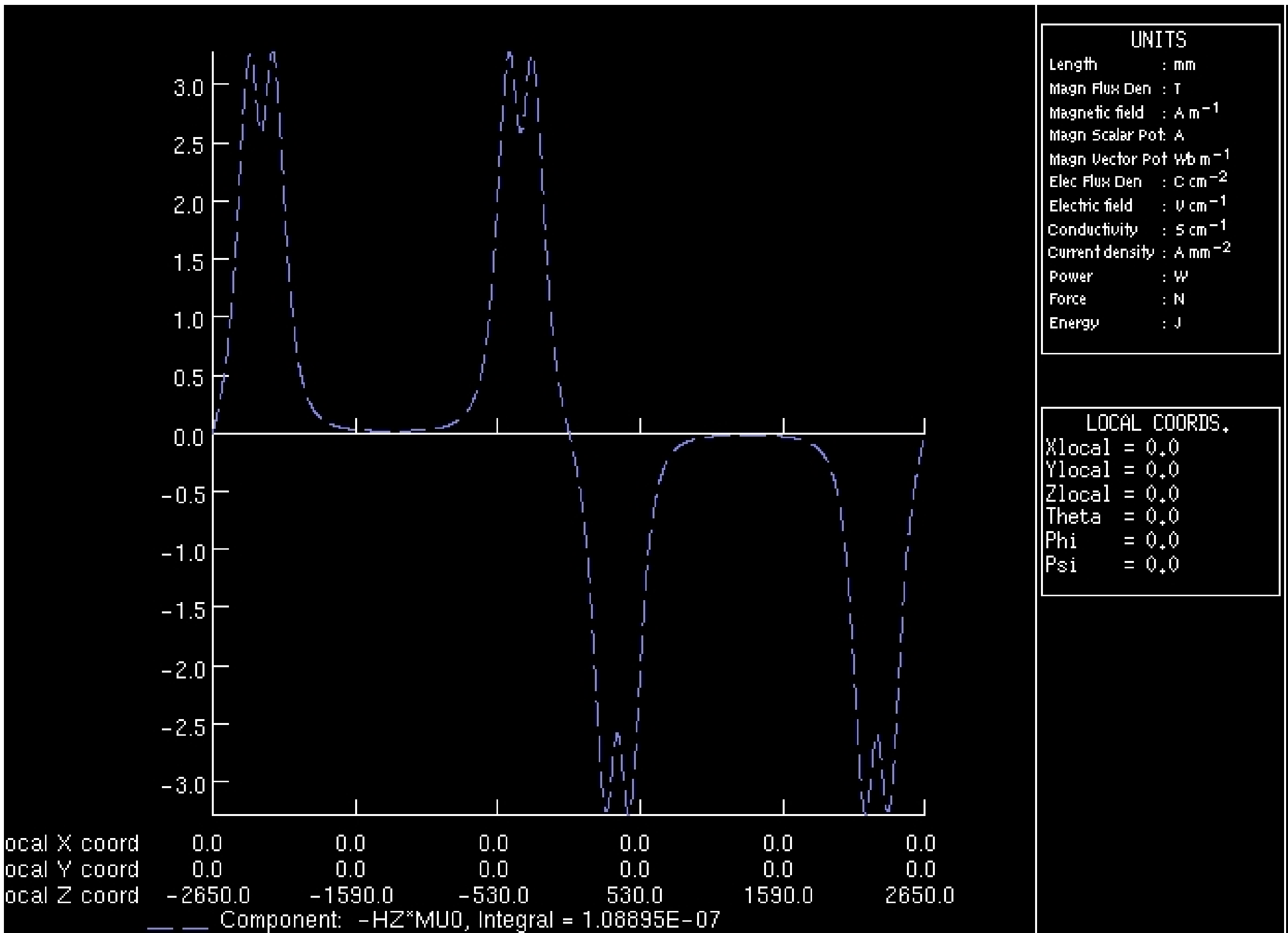
> Makes ring small

Important for BNL site

Note: Bx & By (normal and skew harmonics) are cancelled but Bz (axial field) is not.

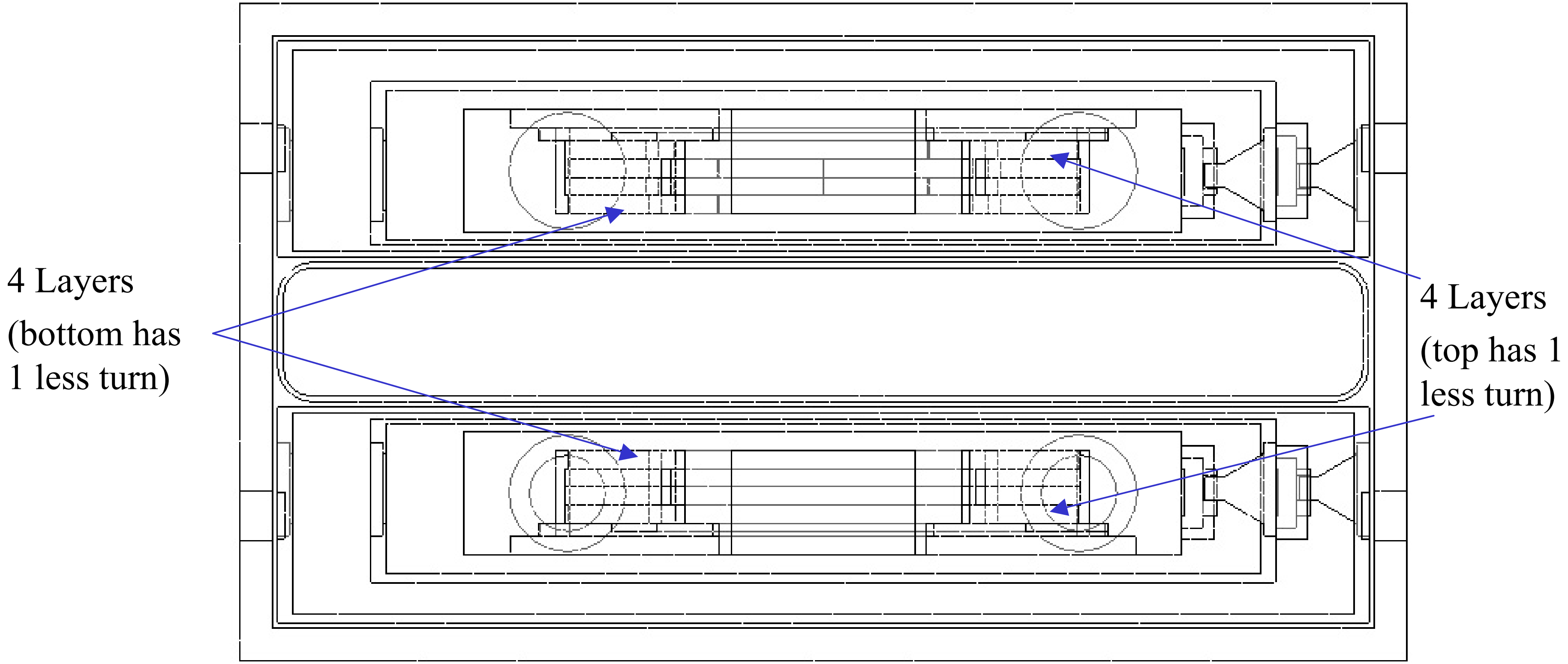
Non-zero Axial Component of the Field





Incorporation of Small Normal Gradient

A small normal quadrupole component is required in magnets for AP reasons

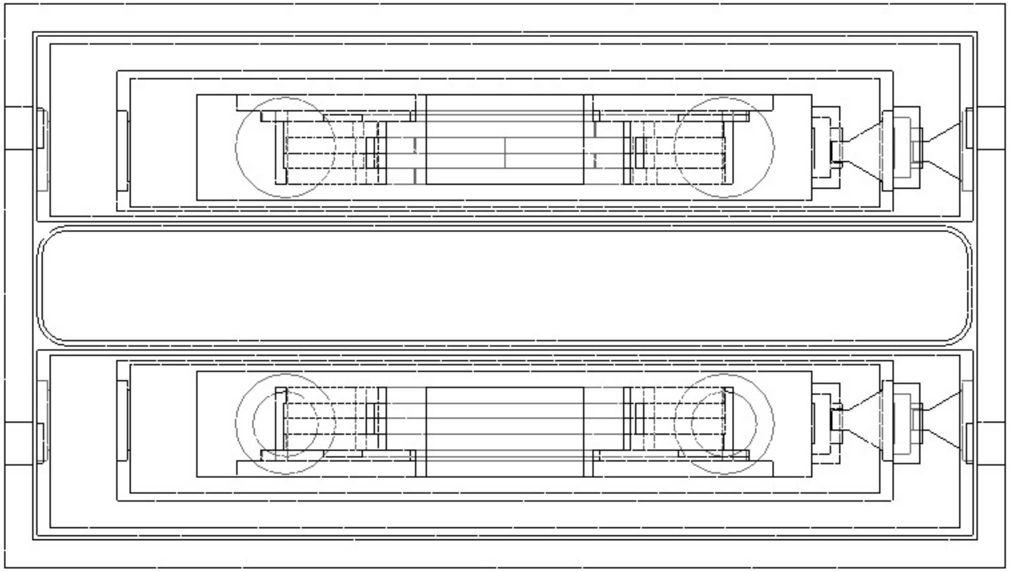


A small quadrupole component is obtained by have one less turn in the layers indicated.

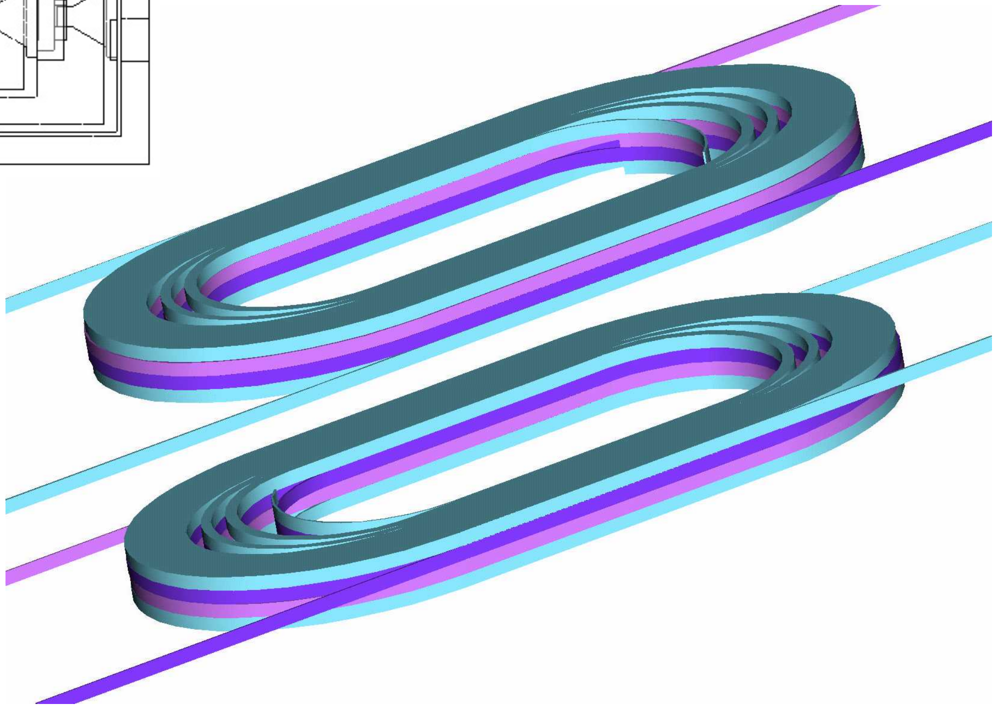
The value will be tuned with spacers, etc.

This structure also helps in carrying conductor from one end to another.

Magnet Construction Plan for Neutrino Factory Storage Ring Dipole Model at BNL



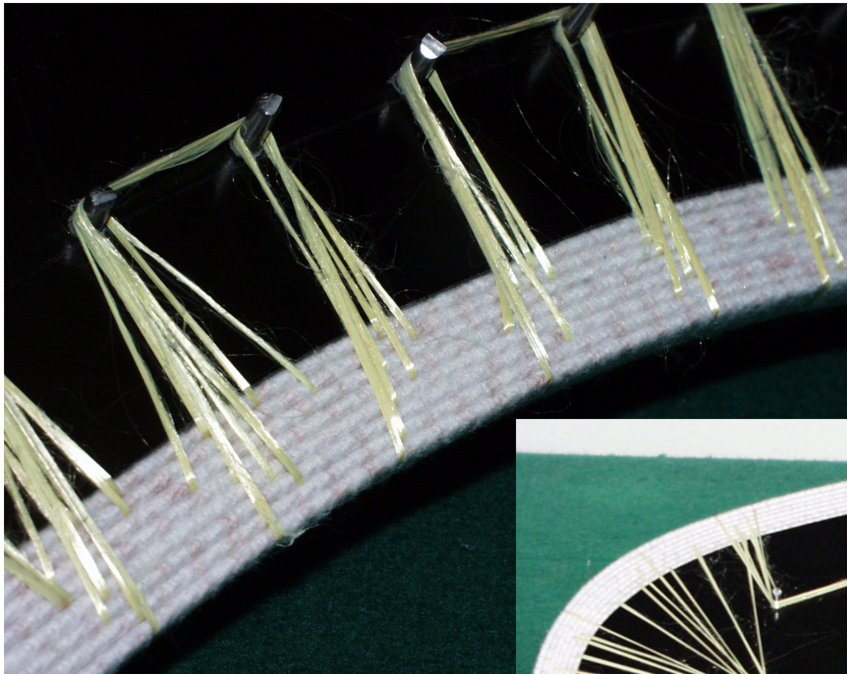
We have got a limited funding under LDRD. With that we are building a series of short coils (length same as in study 2).



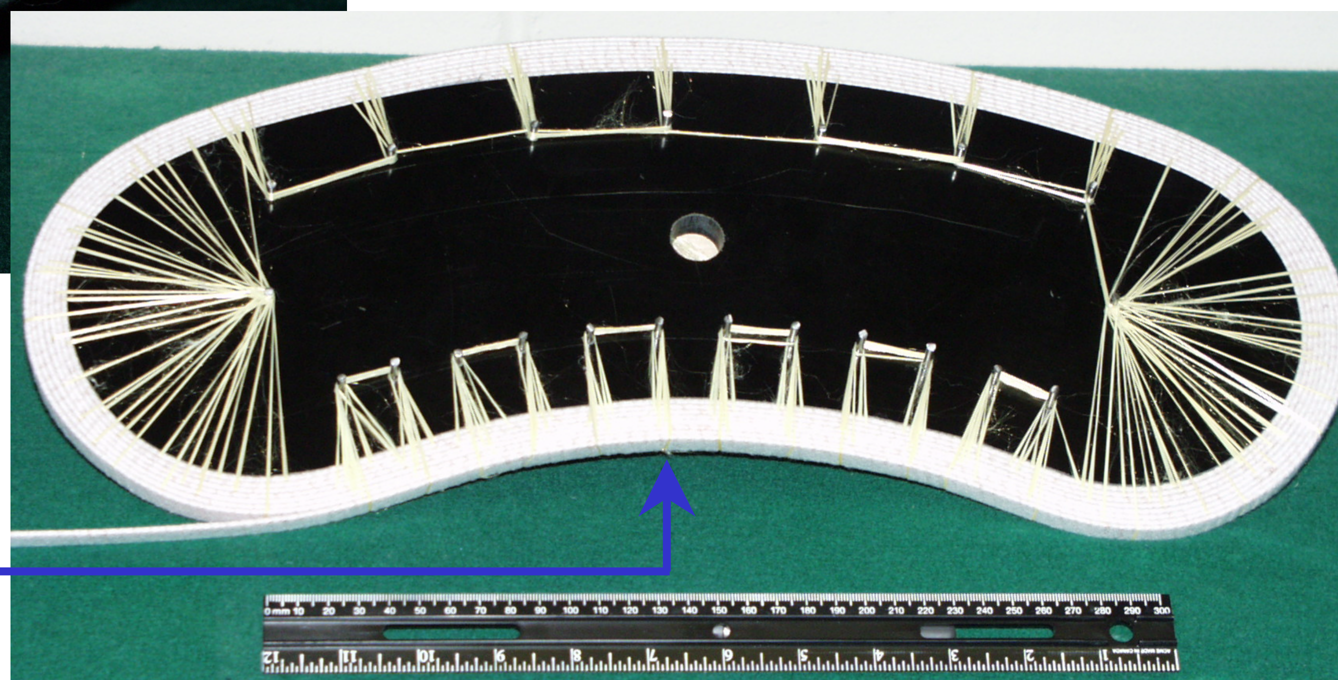
The cross section in the magnet under construction belongs to an earlier design; but all design principles remain the same.

The magnet will be made using ITER cable and therefore would reach a lower (~4 T) field.

Saggitta in Nb3Sn React & Wind Dipole



A new method to obtain large reverse curvature devised with Kavlar strings (John Escallier)



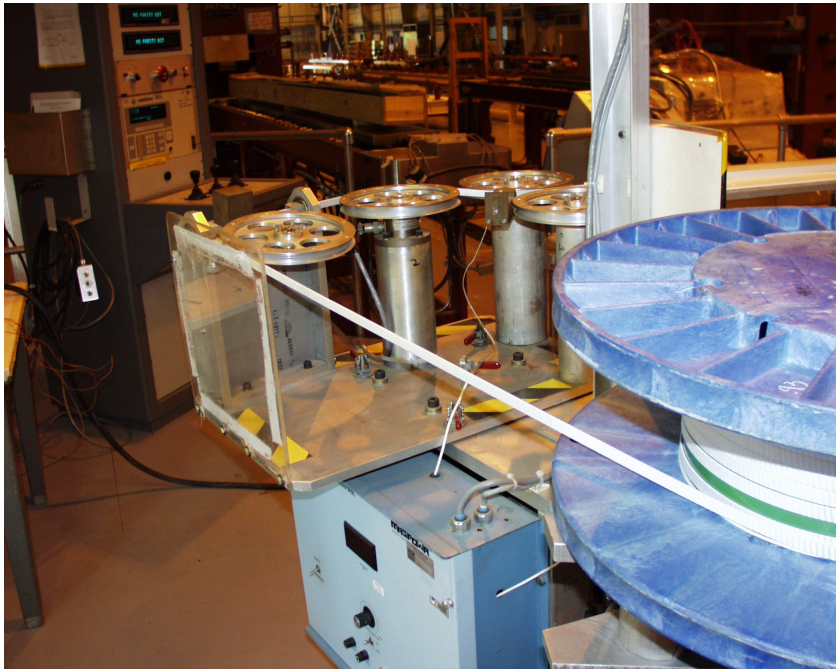
Good for making straight racetrack coils also for obtaining tightly packed turns

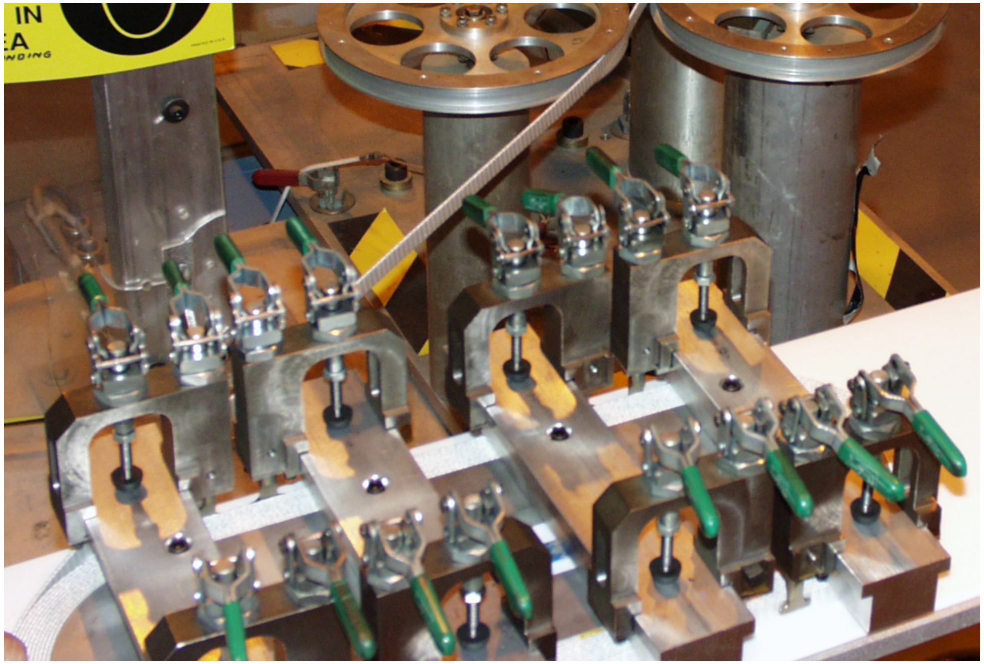
Reverse curvature

Nb_3Sn Cable Coil Winding

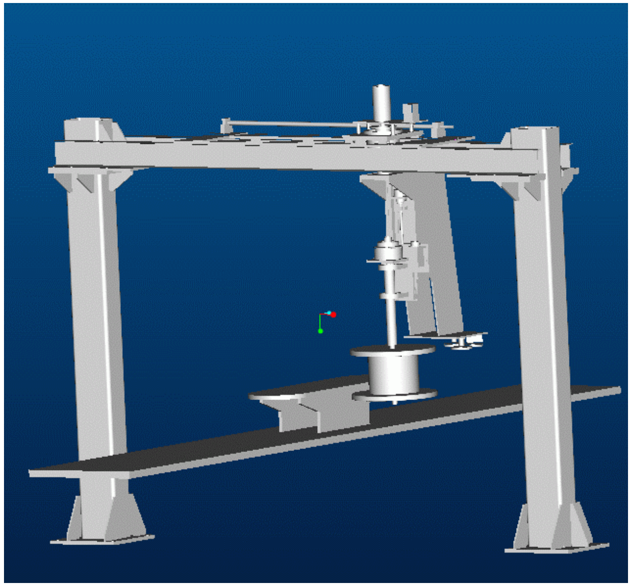
The winding of Nb3Sn racetrack coil for common coil magnet program

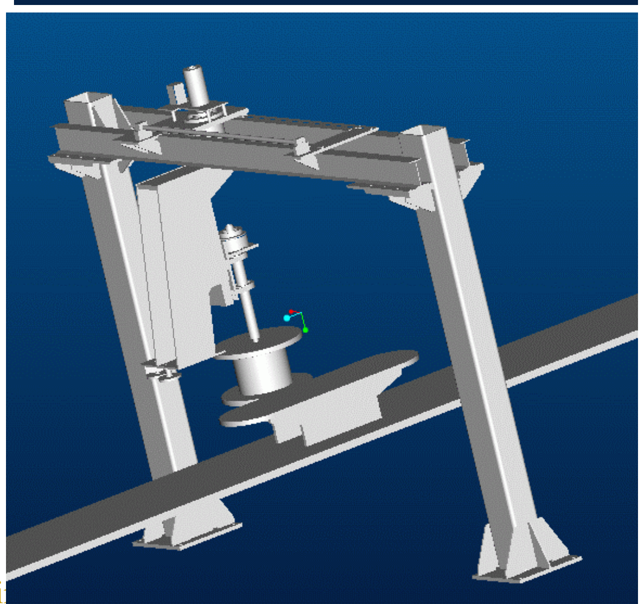
•**Reverse bend have been removed from the above tooling.**

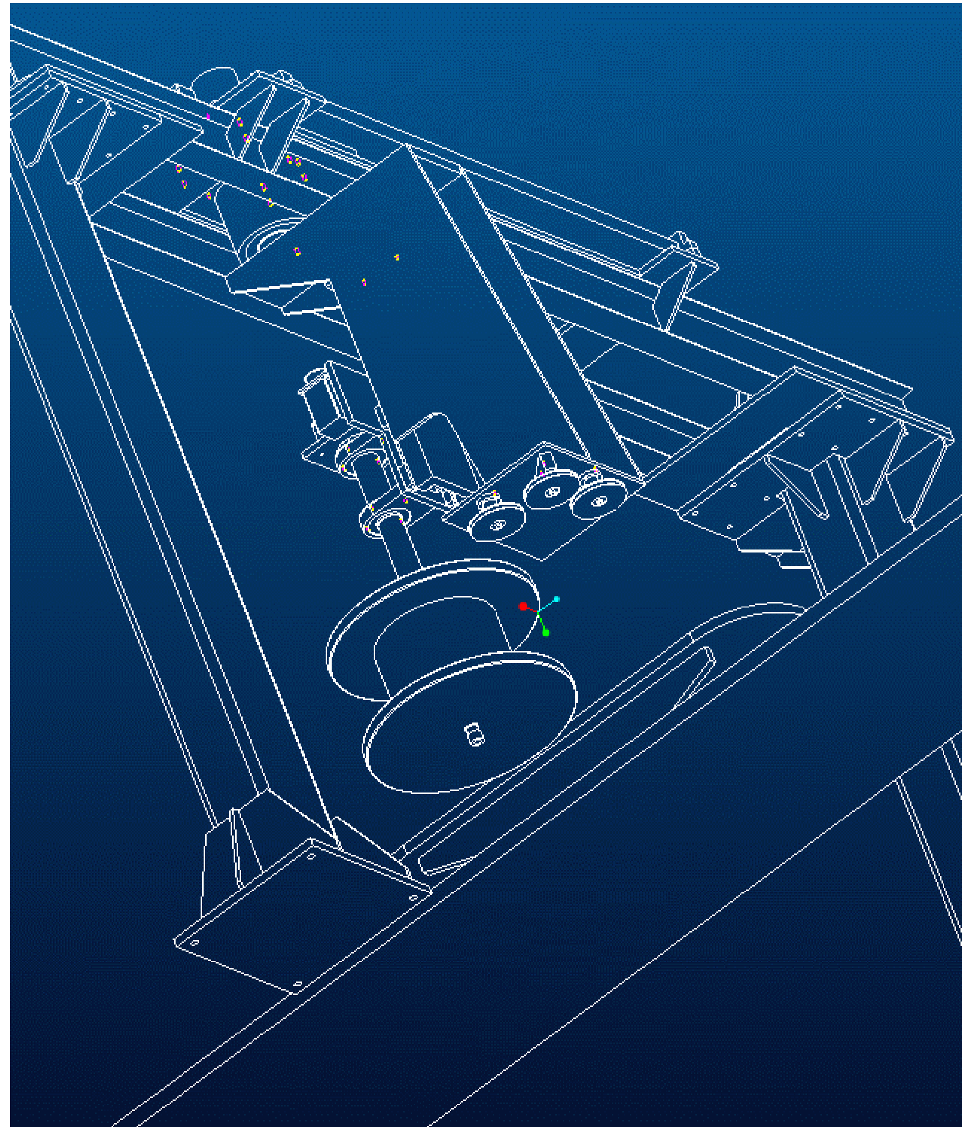




New Versatile Coil Winder Now Under Design







Status and Progress

- **Conceptual design completed**
- **Initial magnetic and mechanical analysis performed**
  – magnet design is strongly coupled with the lattice design

Goals For the Rest of the Year

- Continue on the detailed engineering design (including support structure and cryostat)
- Develop tooling design for winding coils, vacuum impregnation, etc.
- Develop test fixture/setup

Goals For the Next Year

- Build necessary tooling for a testing coils under different configurations
- Build short Nb_3Sn coils with ITER conductor (almost free)
- Test these coils in the following configurations:
  - Dipole

  - Quadrupole

  - Combined function magnet

- Continue work on improving design to make storage ring more compact and more efficient

Basic Parameters for the Neutrino Factory Storage Ring Study 2

Energy: 20 Gev

Circumference: 358.18 m

Length of Arc: 53.09 m

Length of Production Straight: 126 m

No. of cells per arc: 10

Cell length: 5.3 m

Dipole magnetic length: 1.89 m

Design dipole field: 6.93 T

Quench field: ~ 8 T

This field can be raised to over 10 T by adding more conductor and grading it while using state-of-the art Nb3Sn.

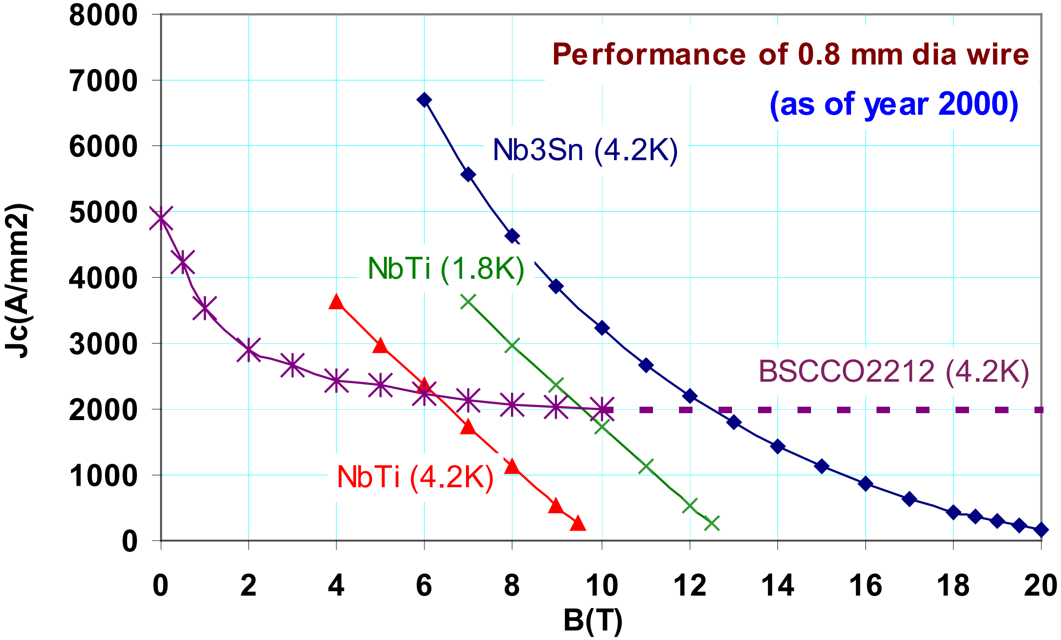
Skew quadrupole magnetic length: 0.76 m

Skew quadrupole gradient: 35 T/m

Mechanical coil length: ~ 0.8 m and ~ 5 m

HTS has a potential of generating even higher fields and dealing better with the large amount of decay products in muon colliders

Expected Performance of HTS-based Magnets



Year 2000 data for J_c at 12 T, 4.2 K

Nb_3Sn: 2200 A/mm^2

BSCCO-2212: 2000 A/mm^2

Near future assumptions for J_c at 12 T, 4.2 K

Nb_3Sn: 3000 A/mm^2 (DOE Goal)

BSCCO-2212: 4000 A/mm^2 (2X from today)

Expected performance of all Nb_3Sn or all HTS magnets at 4.2 K for the same amount of superconductor:

Year 2000 Data	
All Nb_3Sn	All HTS
12 T	5 T
15 T	13 T
18 T	19 T*

*20 T for Hybrid

Near Future	
All Nb_3Sn	All HTS
12 T	11 T
15 T	16 T
18 T	22 T

Cu(Ag)/SC Ratio

BSCCO: 3:1 (all cases)

Nb_3Sn: 1:1 or J_{cu}=1500 A/mm^2

Issues with HTS

Advantages:

• Can work at elevated temperature. For example, in muon collider and IR region magnets where a large energy is deposited from the decay products.

• Has potential for producing very high magnetic fields.

Challenges:

• Large quantities are not available yet

But enough to make test coils and the length of wire available are increasing continuously. Remember HTS is support by other program.

• Unknown field quality issues

We will be measuring them soon.

• High cost

Needs to come down by the time these magnets are needed. Also compare the overall system cost. Consider special applications where cost matters less.

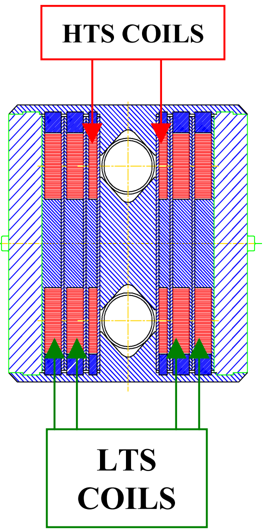
Status:

The performance has reached a level to consider them as a promising candidate.

BNL has started magnet R&D with this challenging material. Results are encouraging.

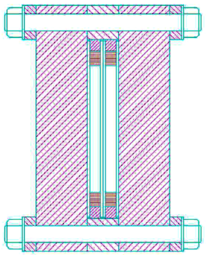
Consider HTS option for magnets that are not required immediately.

HTS Magnet R&D Program at BNL



Primary Goal of the Program:

Develop magnet designs and technology for various applications where HTS has a potential of playing a significant role. Build a ~12.5 Tesla, "React & Wind" Common Coil Magnet to provide a background field to evaluate HTS coil performance at high field.



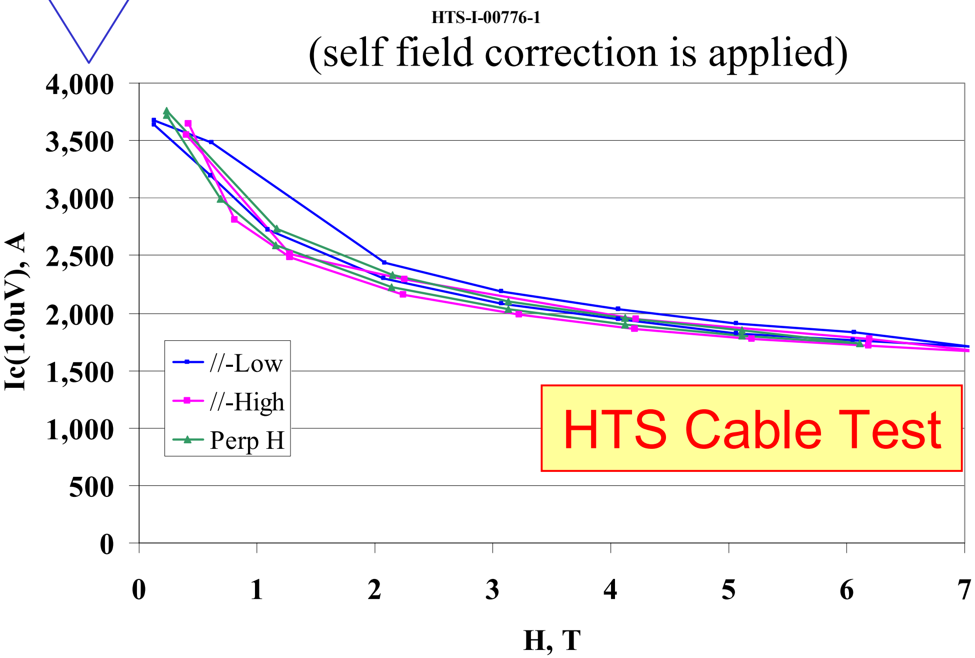
R&D Plan to Develop Technology:

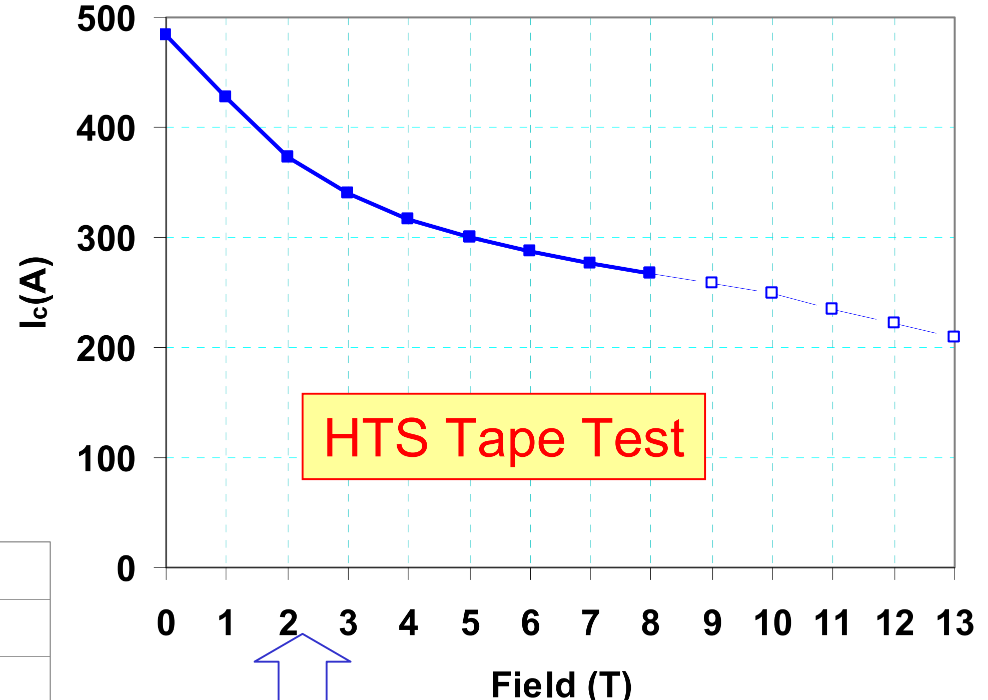
HTS is a new technology. We should expect to make many coils and burn a few to properly understand the technology. We have started a "*mini 10-turn magnet R&D program*" with rapid turn-around to systematically develop the technology with rapid turn-around at a price we can afford. We started out with "React & Wind" Nb_3Sn and went to HTS.

Measured Performance of HTS Cable and Tape As A Function of Field at BNL

Measurement of an earlier "***BSCCO-2212 cable***" at BNL test facility.

Ic is better by over a factor of 2 now. This was a narrow (18 strand) cable. Standard cable will carry much more. Expect 5000 A up to a high field.

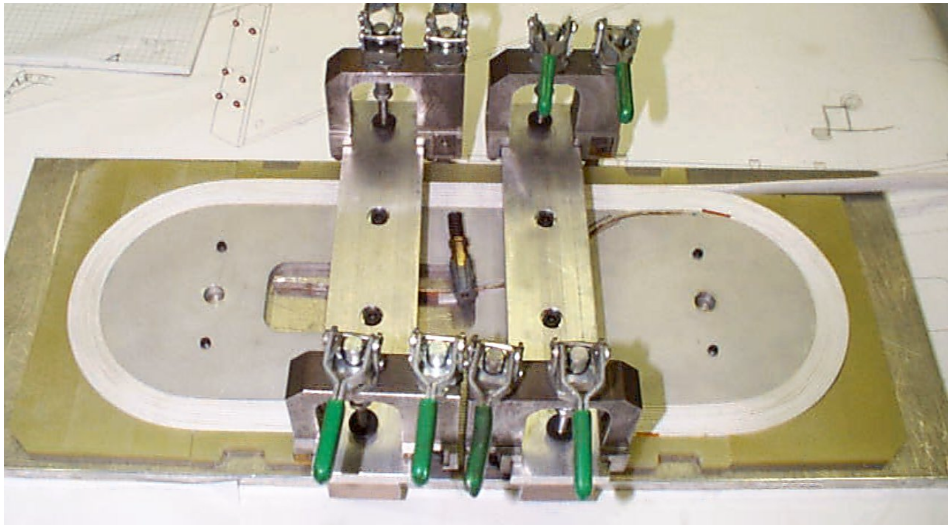




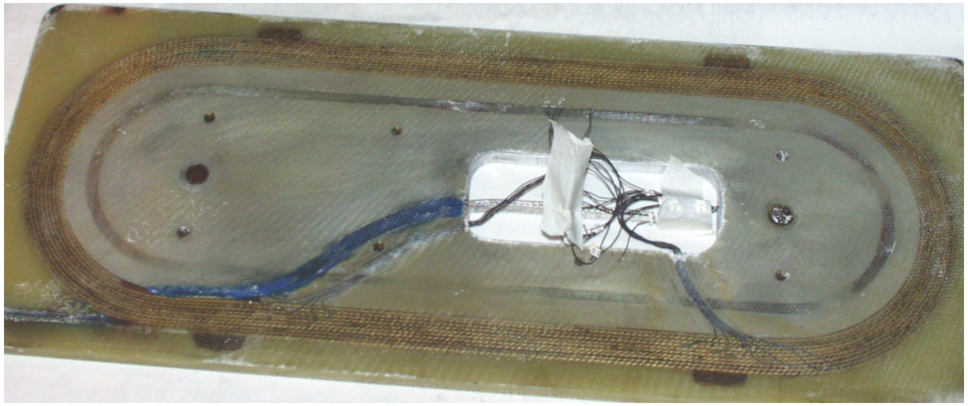
Measurement of "***BSCCO 2223 tape***" wound at 57 mm diameter with applied field parallel (1μV/cm criterion)

(field perpendicular value is ~60%)

Common Coil Magnets With HTS Cable

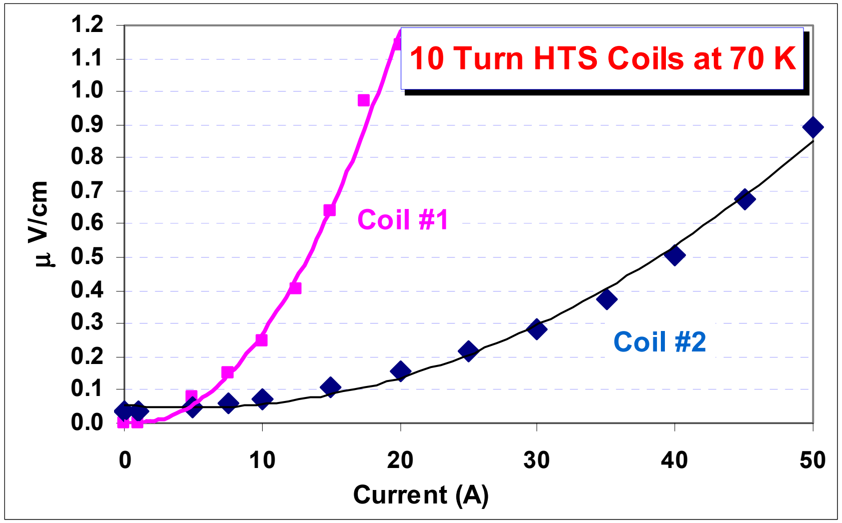


HTS cable coil prior to vacuum impregnation



A coil cassette made with HTS cable after vacuum impregnation and instrumentation

Two coils were tested in Liquid Nitrogen

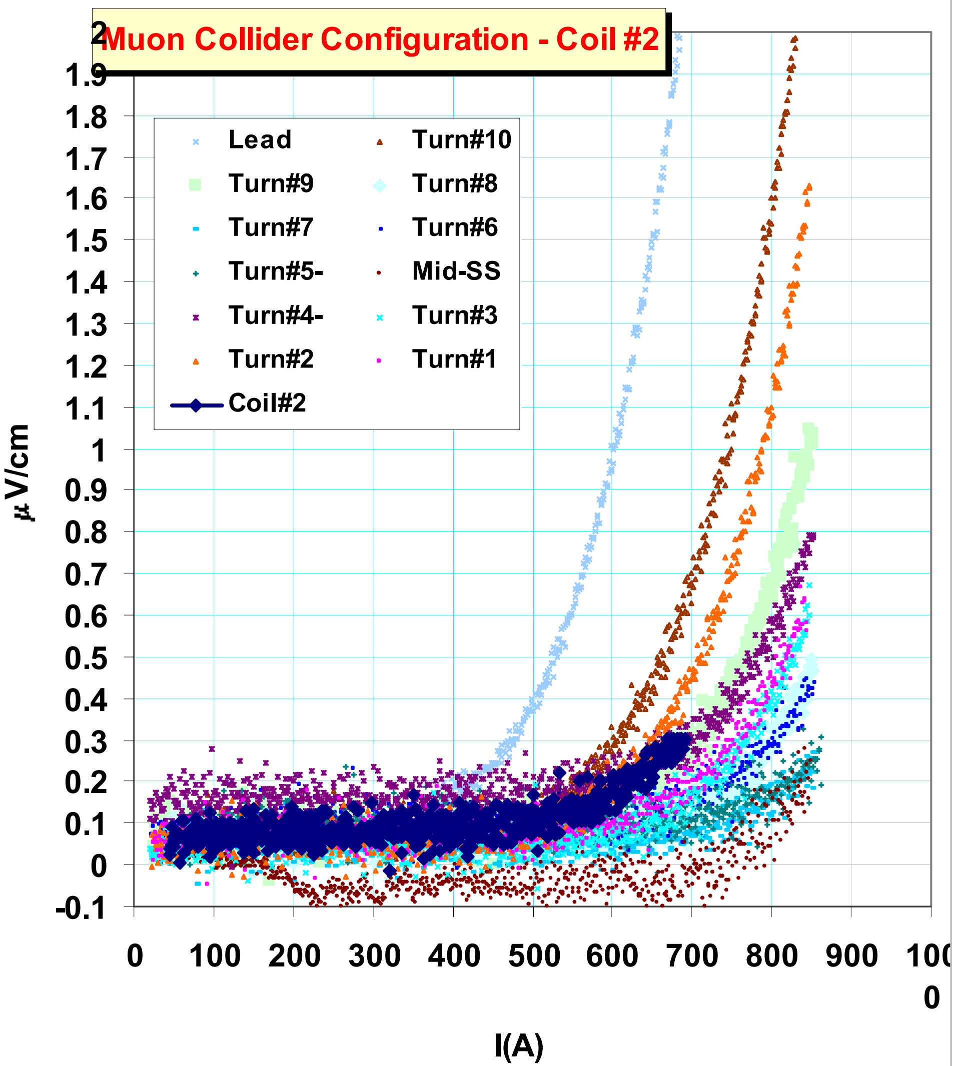


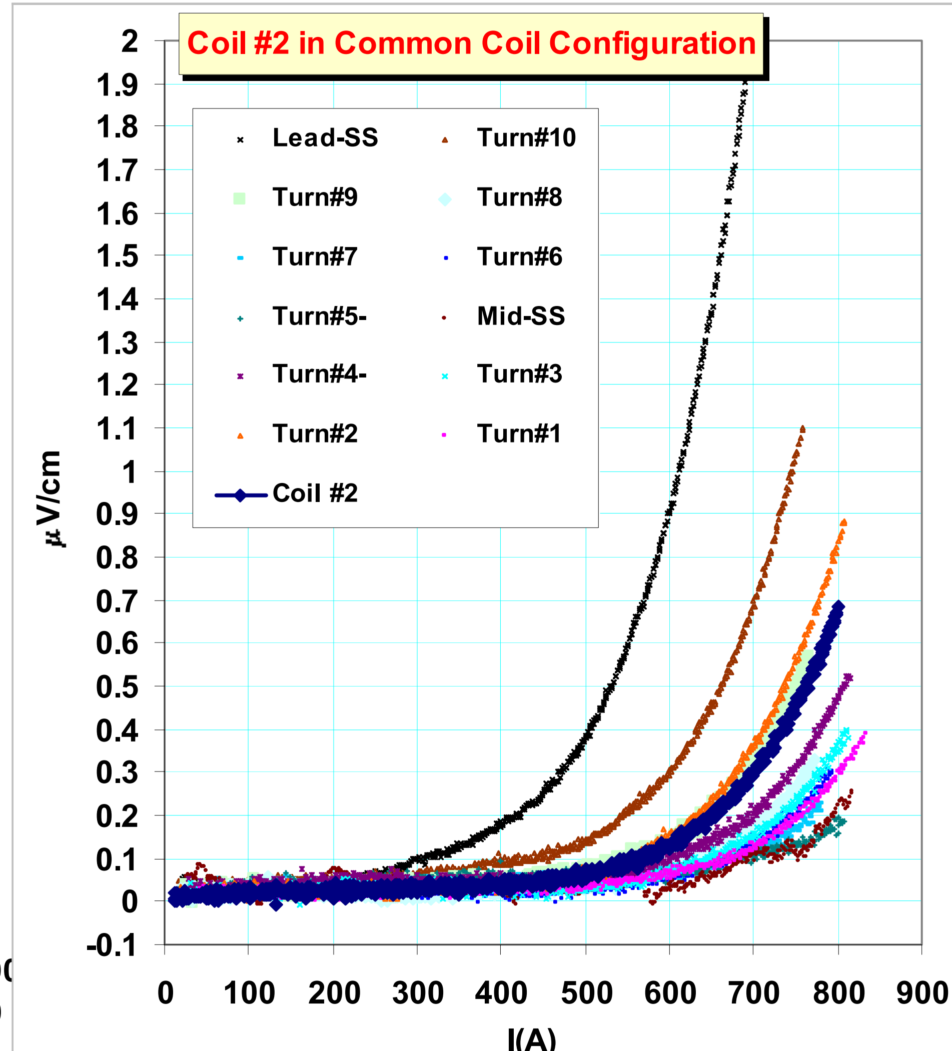
The HTS cables were from two different batches. They behaved differently:

- Different Ic
- Different Tc

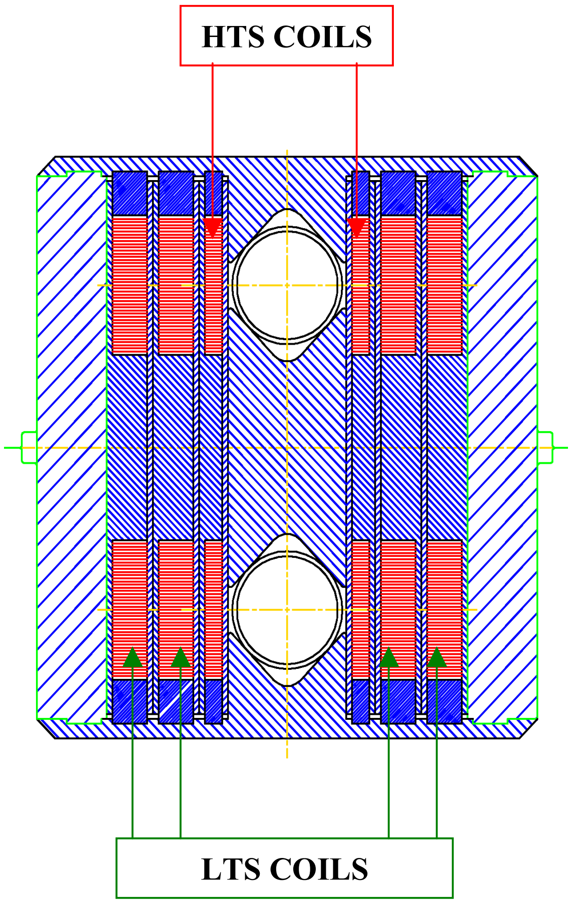
Based on preliminary analysis, no large degradation has been observed.

Results of Coil #2 Tested in Muon Collider and Common Coil Configuration





HTS Coils in a High Field Hybrid R&D Magnet



- Perfect for R&D magnets now.

  HTS coils are subjected to the similar forces that would be present in an all HTS magnet. Therefore, several technical issues will be addressed.

- Field in outer layers is ~2/3 of that in the 1st layer. Use HTS in the 1st layer (high field region) and LTS in the other layers (low field regions).

- Depending on the application, this could be a design for specialty magnets where the performance, not the cost is an issue.

SUMMARY

Racetrack coil magnet designs with open midplane offer an interesting possibility of making high field magnets that can deal with large energy deposition without tungsten liner.

HTS may be a promising technology for future applications where a large amount of energy is deposited by decay products such as in muon collider and interaction region magnets of various colliders.